A proposed search for Sterile Neutrinos with the ICARUS detector at the CERN-PS

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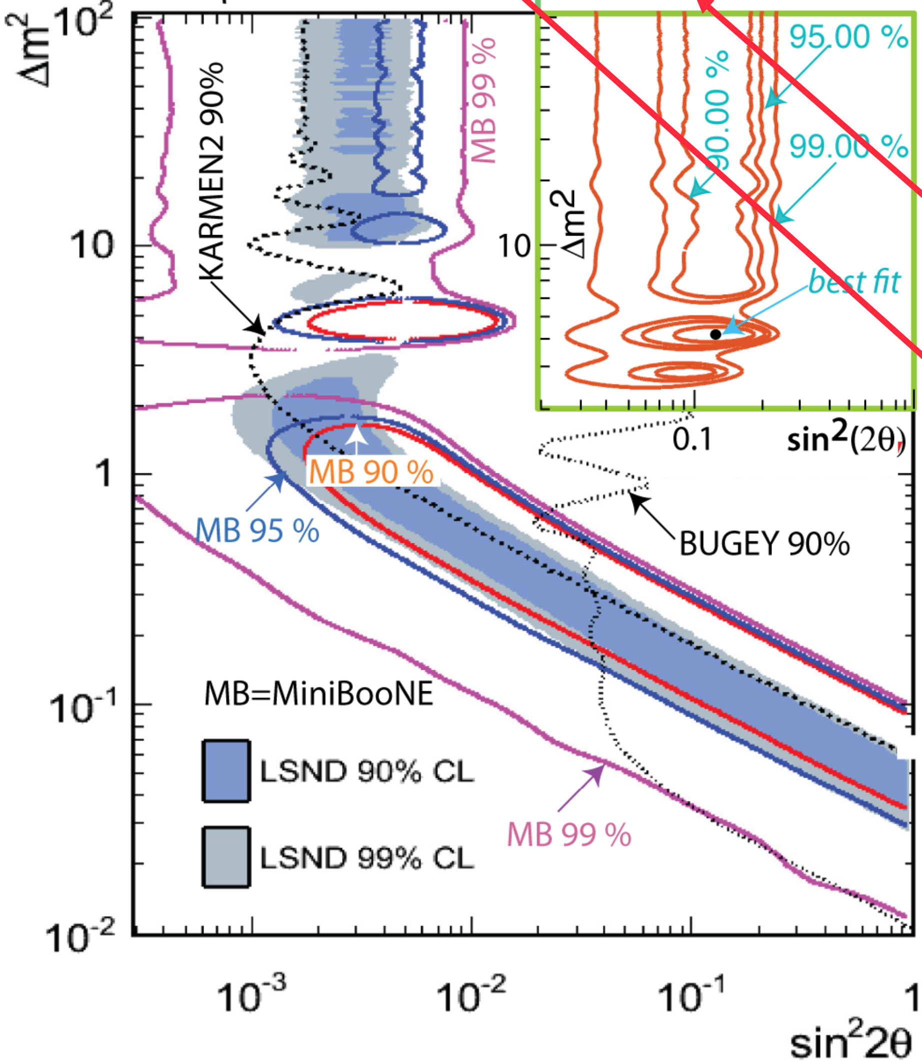
Neutrino oscillation “anomalies”: sterile neutrinos hints

- Two distinct classes of anomalies have been observed:
  - apparent *disappearance signals:* (1) the anti-ν_e events detected from near-by nuclear reactors and (2) from the from Mega-Curie k-capture calibration sources in the Gallium experiments to detect solar ν_e
  - observation for *excess signals* of ν_e electrons from neutrinos from particle accelerators (LNSD/MiniBooNE)
- These experiments may all point out to the possible existence of the at least a fourth non standard neutrino state driving oscillations at a small distances, with typically $\Delta m^2_{new} \geq 1$ eV^2 and relatively large mixing angle with $\sin^2(2\theta_{new}) \approx 0.1$.
- The existence of a fourth neutrino state may be also hinted — or at least not excluded — by cosmological data

A unified approach ?

Combined likelihood for $\nu_\mu \to \nu_e$ oscillation

Combined likelihood for ν_e disappearance



Allowed regions in the plane for combined results:

- The anti-ν_e disappearance rate (right)
- the LSND/MiniBooNE (anti-)ν_e anomaly (left).

While the values of Δm^2_{new} may indeed have a common origin, the different values of $\sin^2(2\theta_{new})$ may reflect within the ≥ 4 neutrinos hypothesis and a mass matrix $U_{(4,k)} \approx 0.1$, where k = μ and e.

In addition, tension between ν_e and anti-ν_e data: CPT violation hints (MINOS)?

The Lar TPC at the CERN-PS

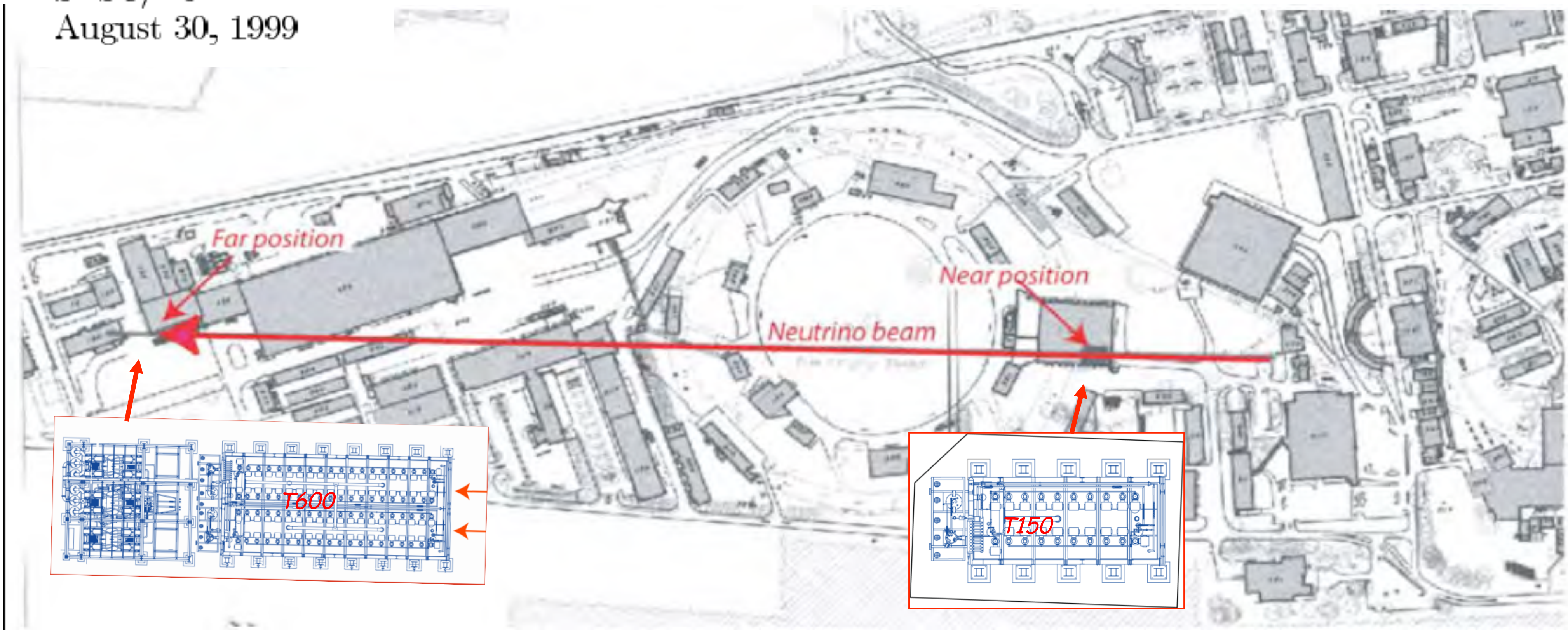
- The direct, unambiguous measurement of an oscillation pattern requires necessarily the (simultaneous) observation at several different distances. It is only in this way that the values of Δm^2 and of $sin^2(2\theta)$ can be separately identified.

- The present proposal at the CERN-PS introduces important new features, *which should allow a definitive clarification of the above described "anomalies"*:
  - "Imaging" detector capable to identify unambiguously all reaction channels with a *"Gargamelle class" LAr-TPC*
  - L/E oscillation paths lengths to ensure appropriate matching to the Δm^2 window for the expected anomalies.
  - Interchangeable ν and anti-ν focussed beams
  - Very high rates due to large masses, in order to record relevant effects at the % level ($>10^6\ \nu_\mu$, $\approx 10^4\ \nu_e$)
  - Both initial ν_e and ν_μ components cleanly identified.

Two LAr-TPC detectors at the CERN-PS neutrino beam

CERN-SPSC/99-26
SPSC/P311
August 30, 1999

SEARCH FOR $\nu_\mu \rightarrow \nu_e$ OSCILLATION
AT THE CERN PS

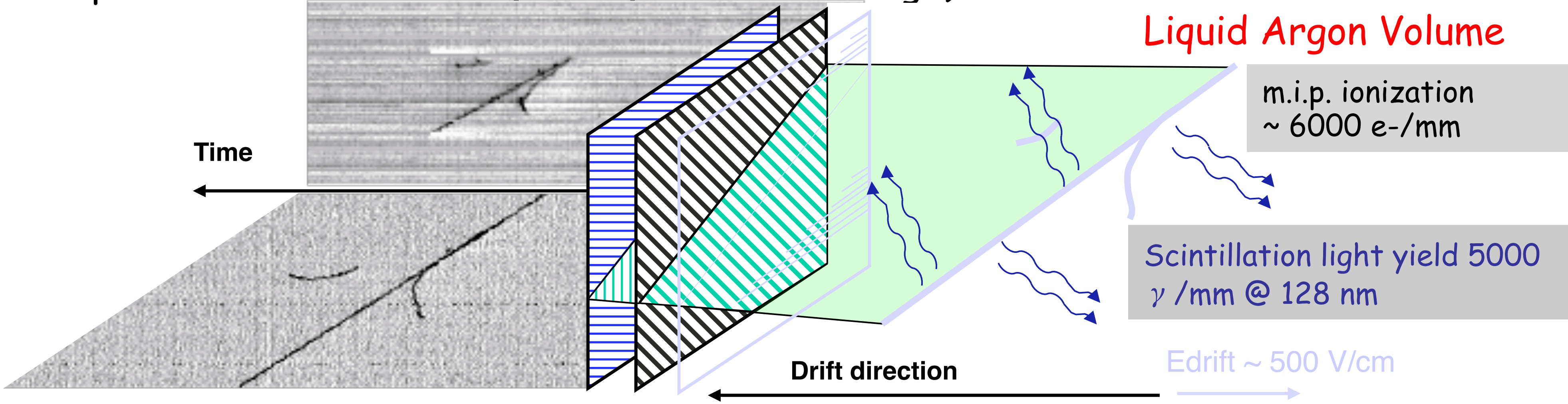


Two positions are foreseen for the detection of the neutrinos
The far (ICARUS-T600) location at 850 m from the target: L/E ~ 1 km/GeV;
The additional detector and new location at a distance of 127 m from the target: L/E 0.15 km/GeV

A powerful detection technique

The Liquid Argon Time Projection Chamber [C. Rubbia: CERN-EP/77-08 (1977)] first proposed to INFN in 1985 [ICARUS: INFN/AE-85/7] capable of providing a 3D imaging of any ionizing event (“electronic bubble chamber”) with in addition:

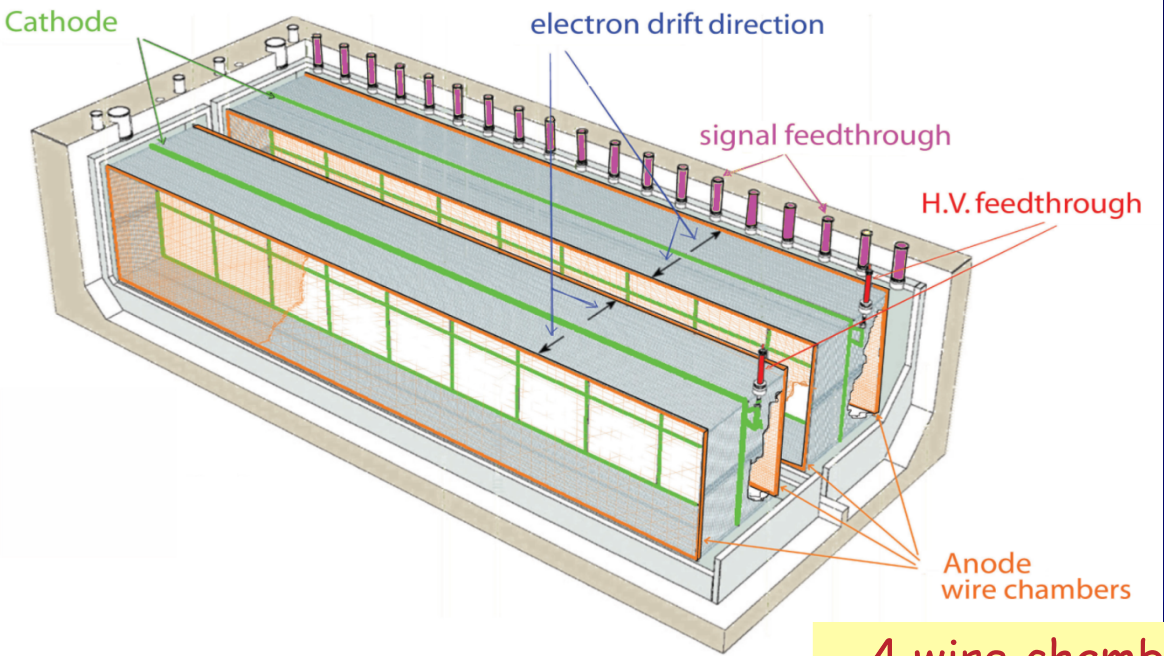
- continuously sensitive, self triggering
- high granularity (~ 1 mm)
- excellent calorimetric properties
- particle identification (through dE/dx vs range)

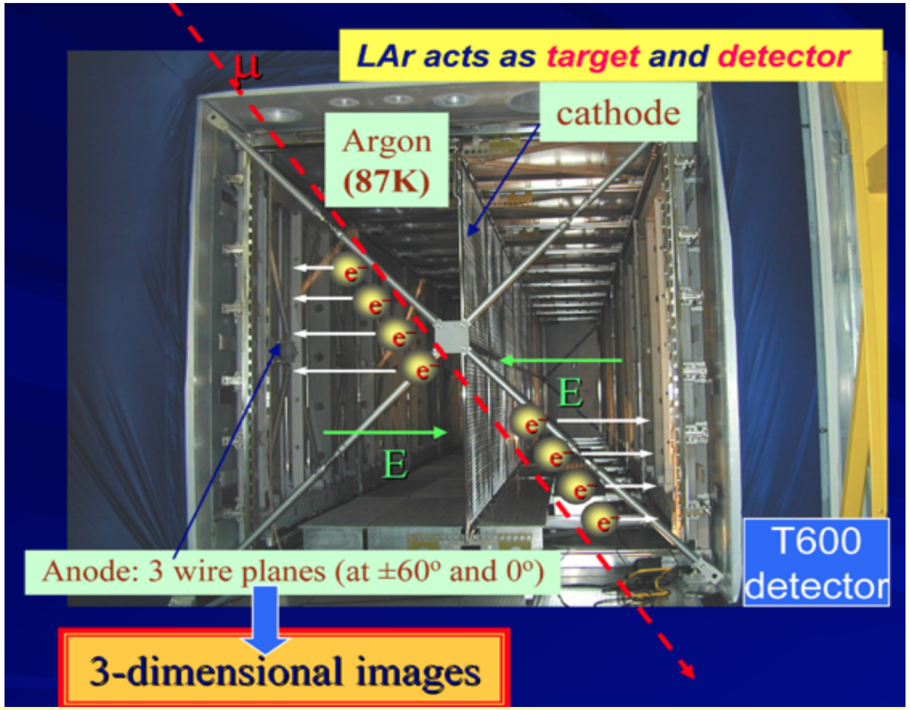


Electrons from ionizing track are drifted in LAr by E_{drift}. They traverse transparent wire arrays oriented in different directions where induction signals are recorded. Finally electron charge is collected by last (collection) plane.

Key feature: LAr purity from electro-negative molecules (O_2, H_2O,CO_2).
Target: 0.1 ppb O_2 equivalent= 3 ms lifetime (4.5 m drift @ E_{drift} = 500 V/cm).

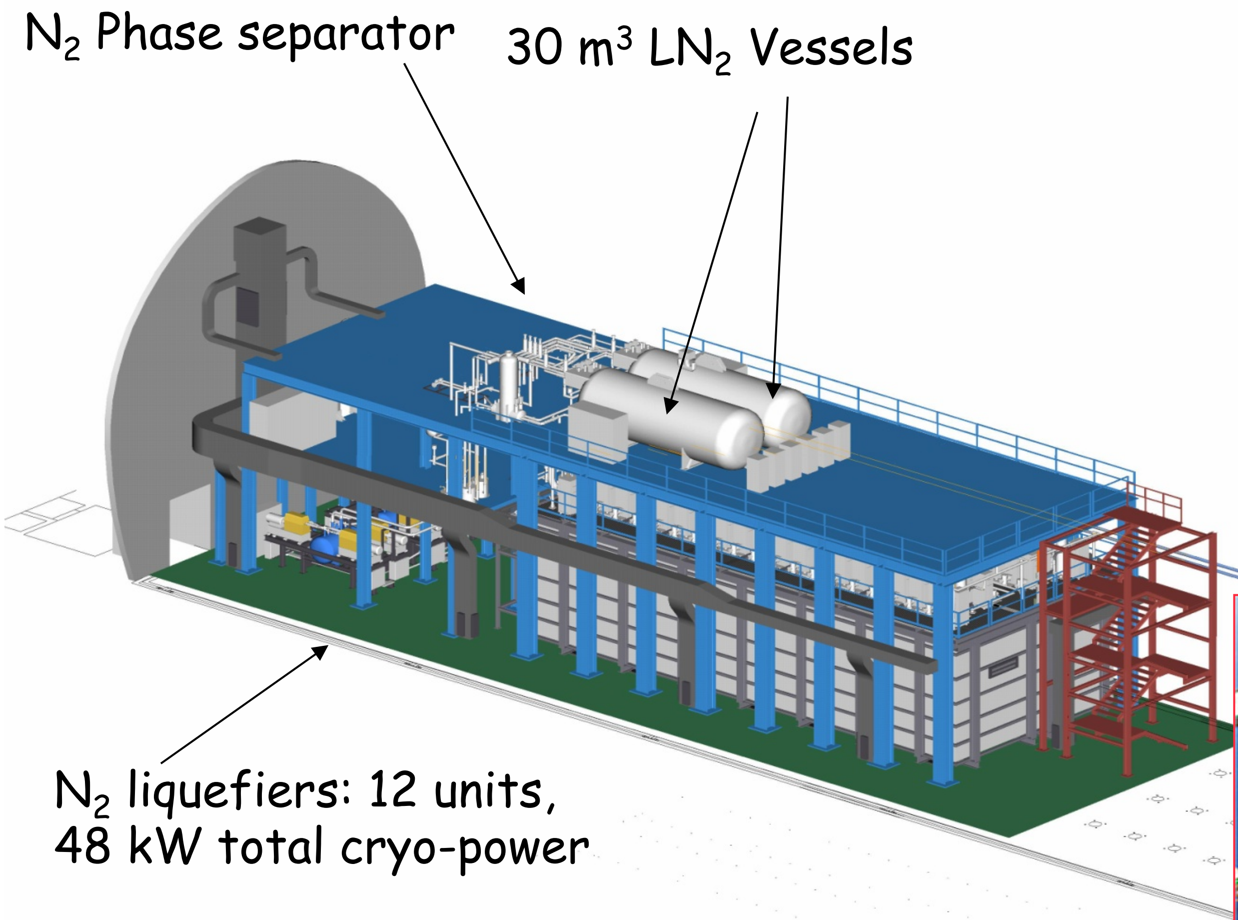
The ICARUS T600 detector

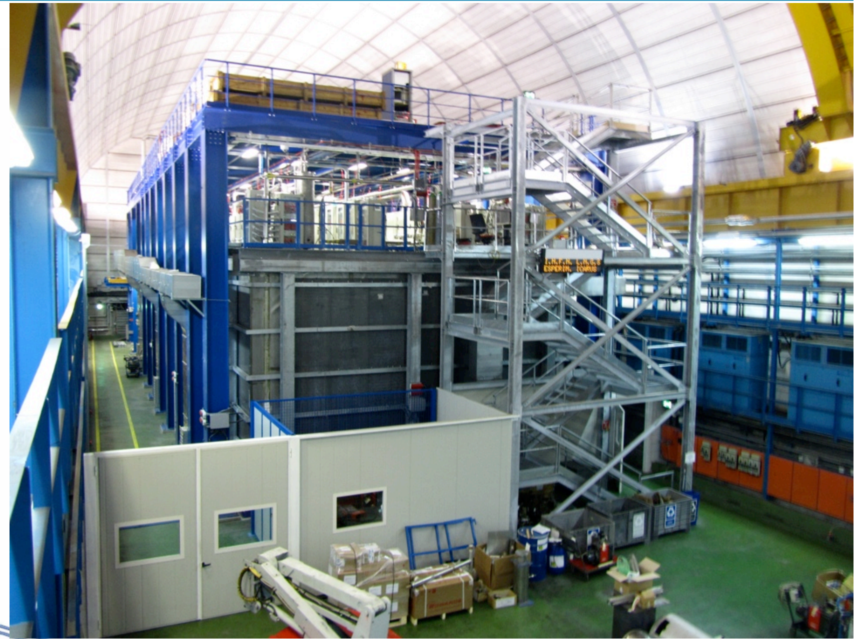




- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m
  - HV = -75 kV E = 0.5 kV/cm
  - vdrift = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes / chamber, wires @ 0, ±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- PMT for scintillation light:
  - (20+54) PMTs, 8" Ø
  - VUV sensitive (128nm) with wave shifter (TPB)

ICARUS T600 in LNGS Hall B





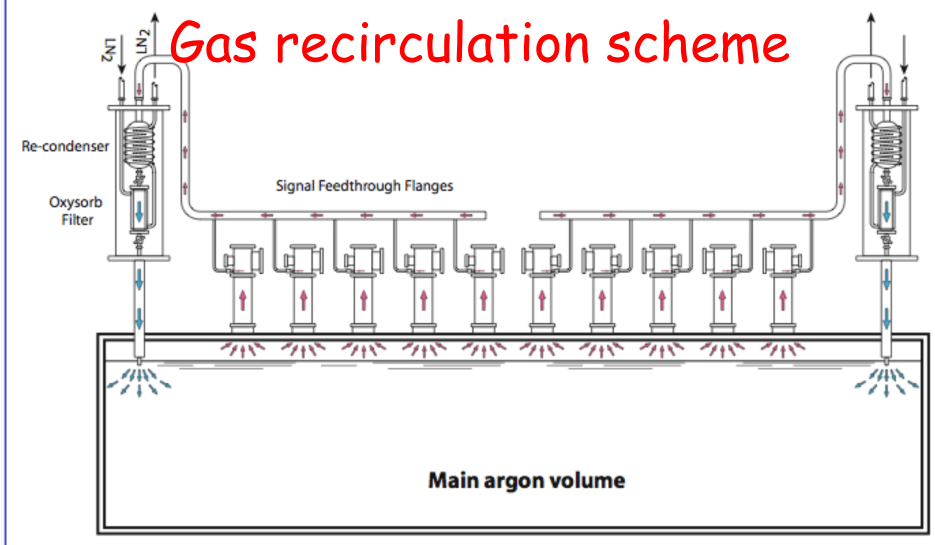
Detector activated on 27 May 2010

Optimization phase in summer 2010

Data taking in stable condition since 01 Oct. 2010

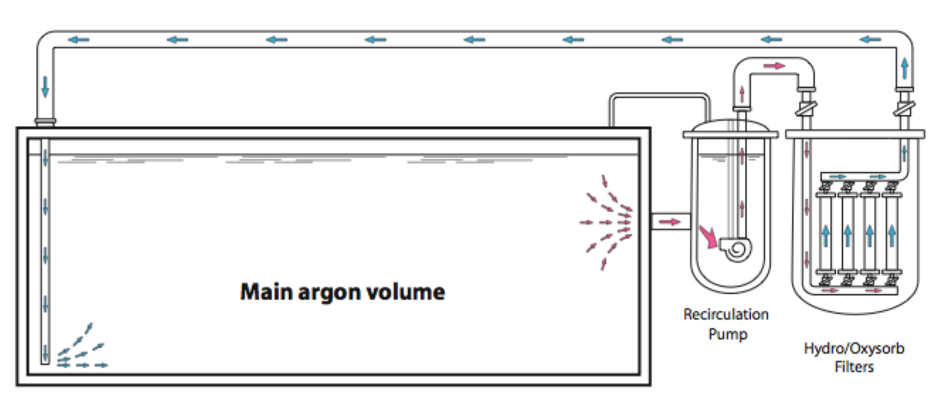
LAr Purification in T600

- The presence of electron trapping polar impurities attenuates the electron signal as $\exp(-t_D/\tau_{ele})$
- τ_{ele} ~ 300 μs / ppb (O_2 equivalent).
- Because of temperature (87 K) most of the contaminants freeze out spontaneously. Main residuals: O_2, H_2O, CO_2.
- Recirculation/purification (100 Nm^3/h) of the gas phase (~40 Nm^3) to block the diffusion of the impurities from the hot parts of the detector and from micro-leaks on the openings (typically located on the top of the device) into the bulk liquid.
- Recirculation/purification (4 m^3/h) of the bulk liquid volume (~550 m^3) to efficiently reduce the initial impurities concentration (can be switched on/off).



Gas recirculation scheme

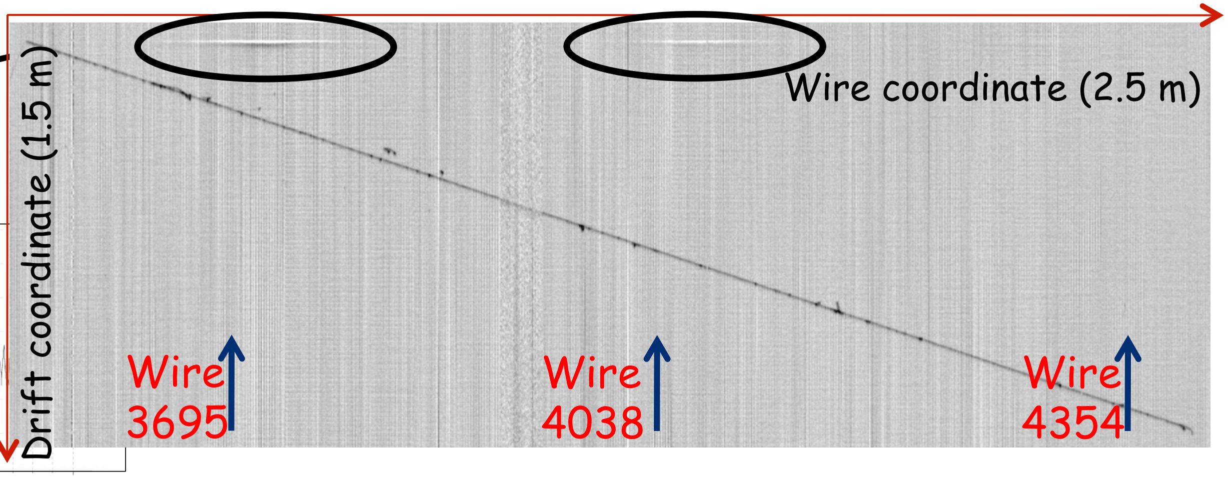
Liquid recirculation scheme



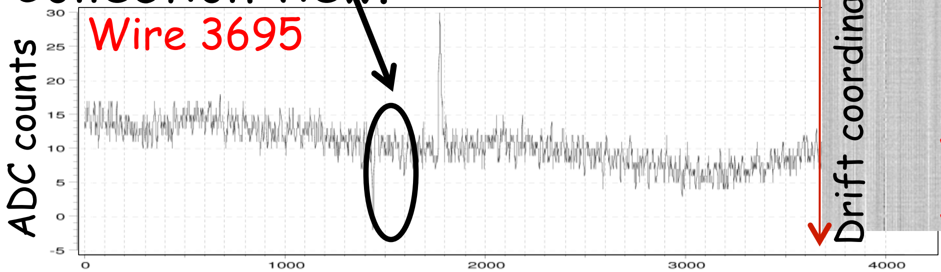
LAr purity measurement with muon crossing tracks

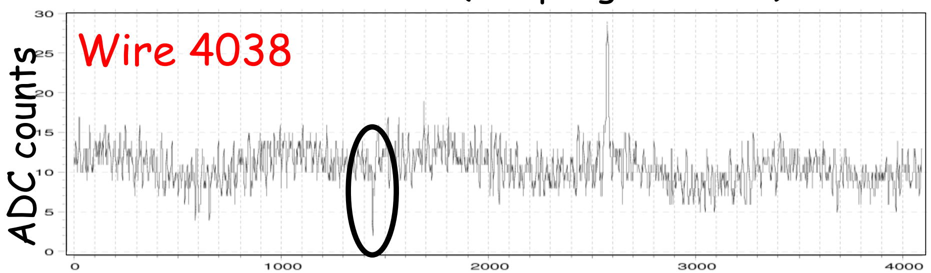
Charge attenuation along track allows event-by-event measurement of LAr purity.

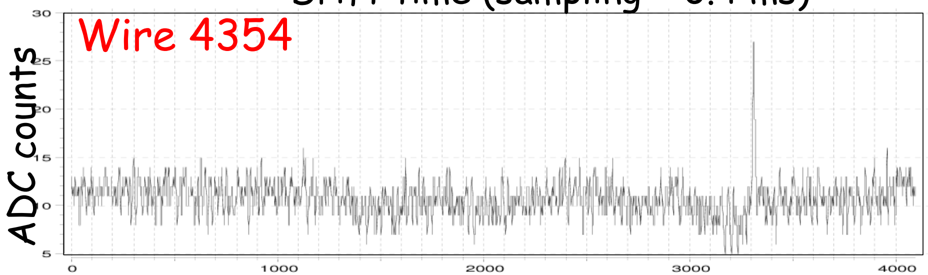
T = 0 estimated by
induction of PMT signal on
Collection view.



Run 10139 Event 8961 Collection view



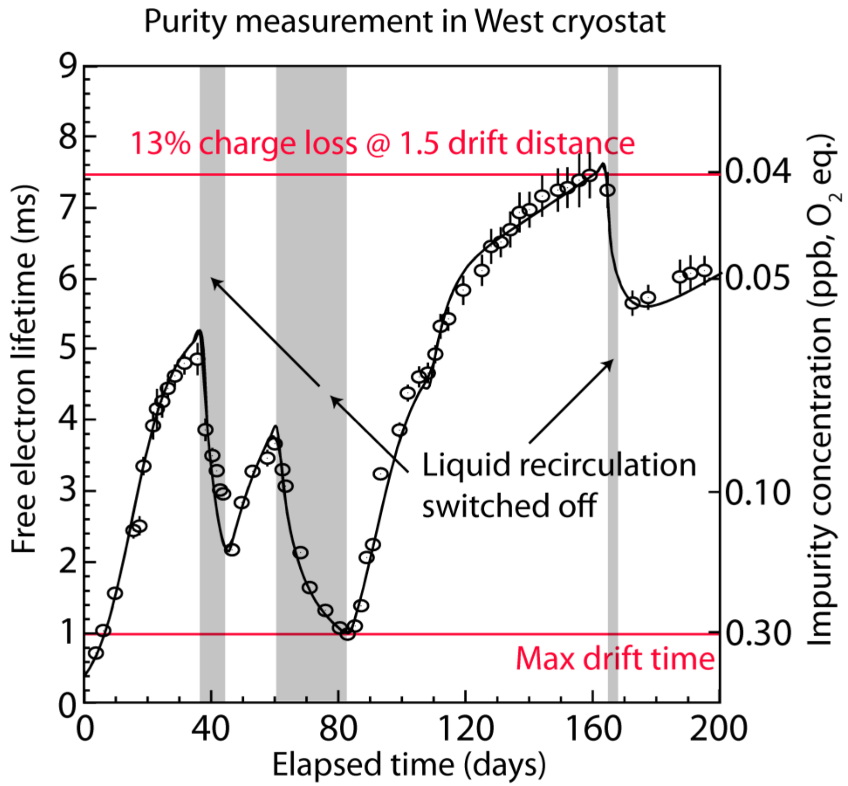


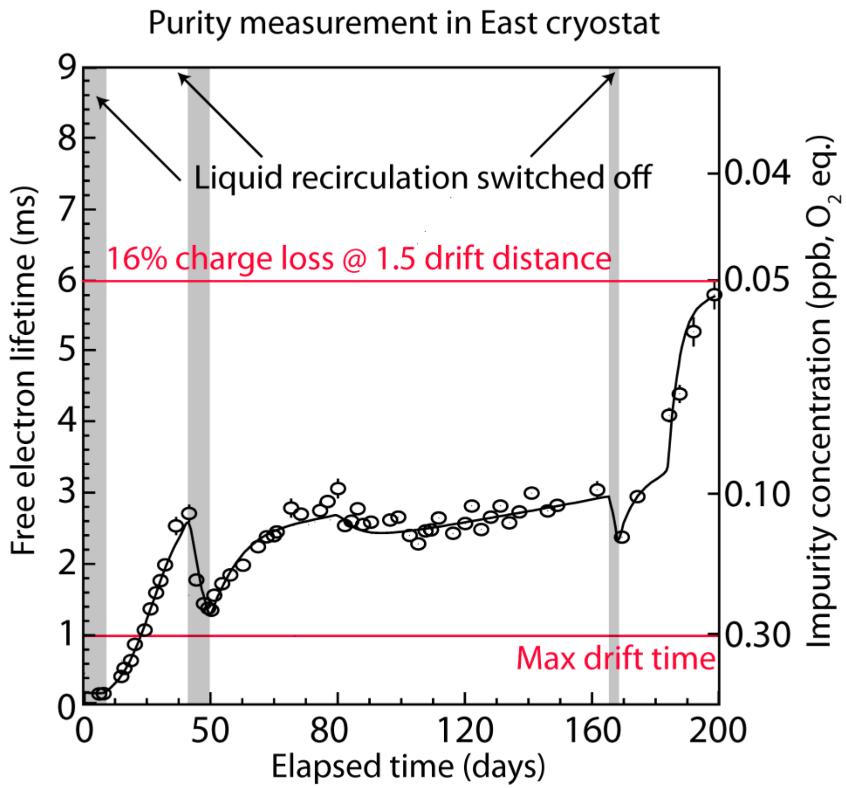


Pulse height for 3 mm m.i.p.
~ 15 ADC # (15000 electrons)

Noise r.m.s.
~ 1.5 ADC # (1500 electrons)

LAr purity time evolution





Simple model: uniform distribution of the impurities, including internal degassing, decreasing in time, constant external leak and liquid purification by recirculation.

$$dN/dt = -N/\tau_R + k + k_I \exp(-t/\tau_I)$$

τ_{ele} [ms] = 0.3 / N[ppb O_2 equivalent]

τ_R: recirculation time for a full detector volume

k_I and τ_I : related to the total degassing internal rate

τ_R: 2 m^3/h corresponding to ≈ 6 day cycle time

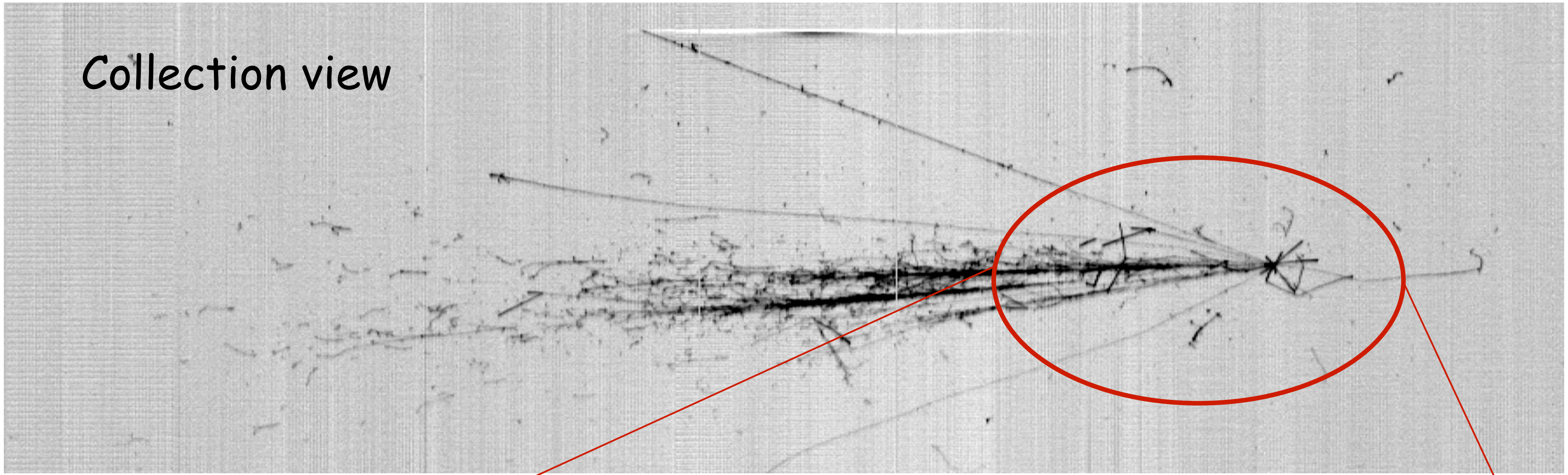
k : related to the external leaks

ICARUS T600 physics potential @ LNGS

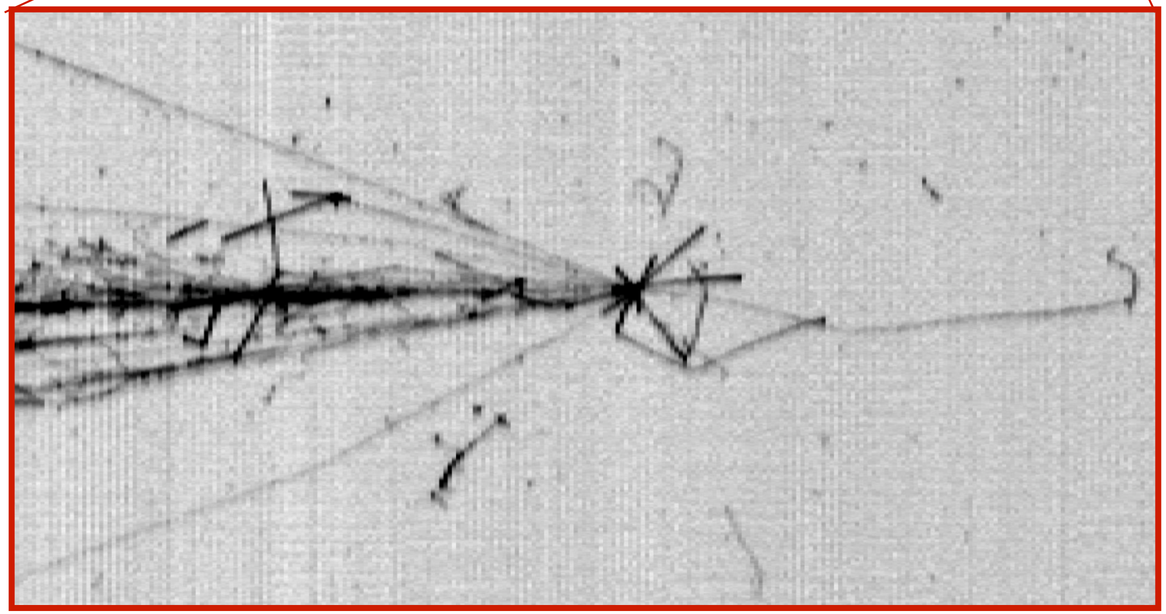
- ICARUS T600: **major milestone** towards realization of large scale LAr detector. Interesting physics in itself: unique imaging capability, spatial/calorimetric resolutions and e/π^0 separation → **events "seen in a new Bubble chamber like" way**.
- CNGS ν events collection (beam intensity 4.5 10^{19} pot/year, E_ν ~ 17.4 GeV):
  - 1200 ν_μ CC event/year;
  - ~ 8 ν_e CC event/year;
  - observation of ν_τ events in the electron channel, using kinematical criteria;
  - search for sterile ν in a fraction of the LSND parameter space (deep inelastic ν_e CC events excess).
- "Self triggered" events collection:
  - ~ 80 events/y of unbiased atmospheric ν CC;
  - zero background proton decay with 3 x 10^{32} nucleons for "exotic" channels.

CNGS neutrino interactions in ICARUS T600

Drift time coordinate (1.4 m)



Wire coordinate (8 m)

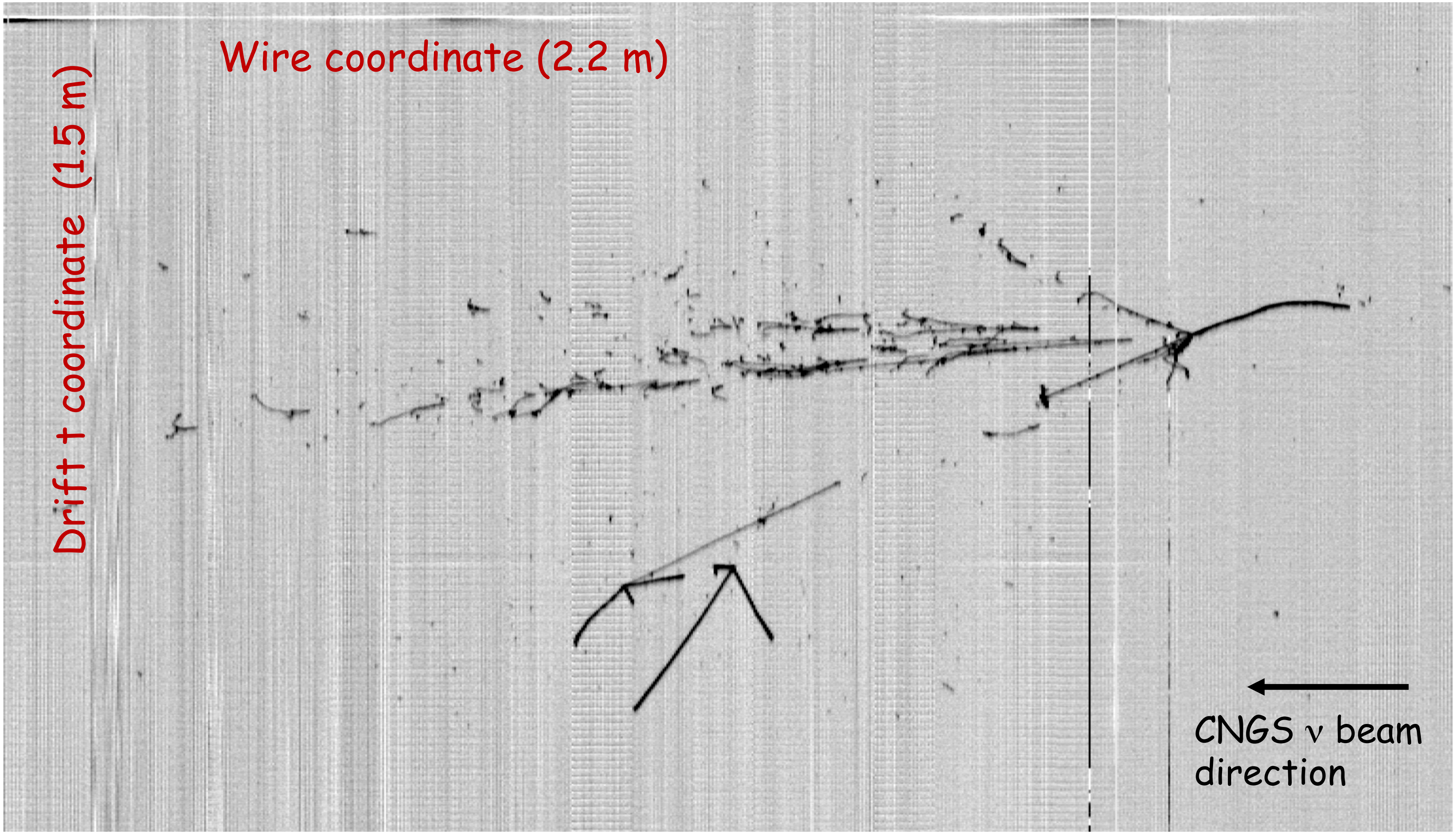


CNGS ν beam direction

←

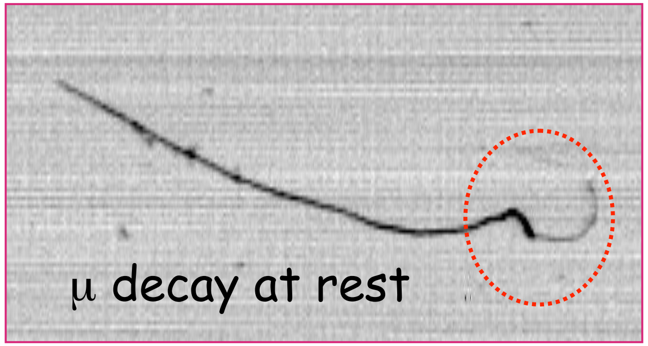
ν_μ CC

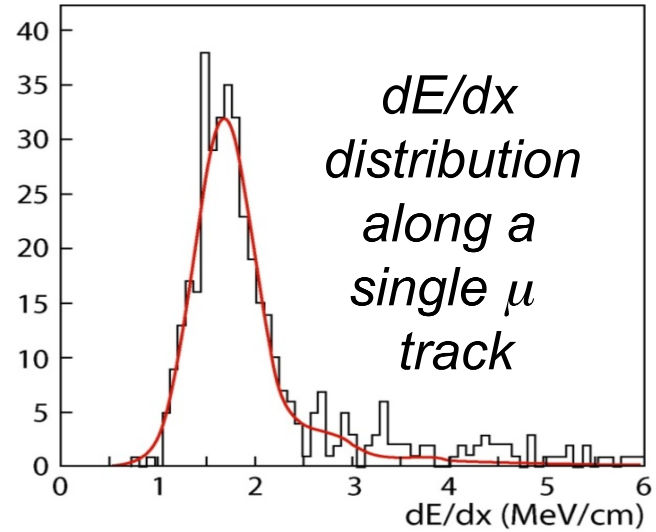
CNGS NC interaction candidate



LAr-TPC performance

- Tracking device:
  - precise event topology ($\sigma_{x,y} \sim 1$mm, $\sigma_z \sim 0.4$mm)
  - μ momentum measurement via multiple scattering: $\Delta p/p$ ~10-15% depending on track length and p
- Measurement of local energy deposition dE/dx:
  - e/γ separation (2% X_0 sampling);
  - particle ID by means of dE/dx vs range
  - e/π^0 discrimination at 10^{-3} by γ conversion from vertex, π^0 mass and dE/dx measurements with 90 % electron identification efficiency
  - NC/CC rejection at 10^{-3} level retaining 90 % ne CC
- Total energy reconstruction by charge integration:
  - full sampling, homogeneous calorimeter with excellent accuracy for contained events



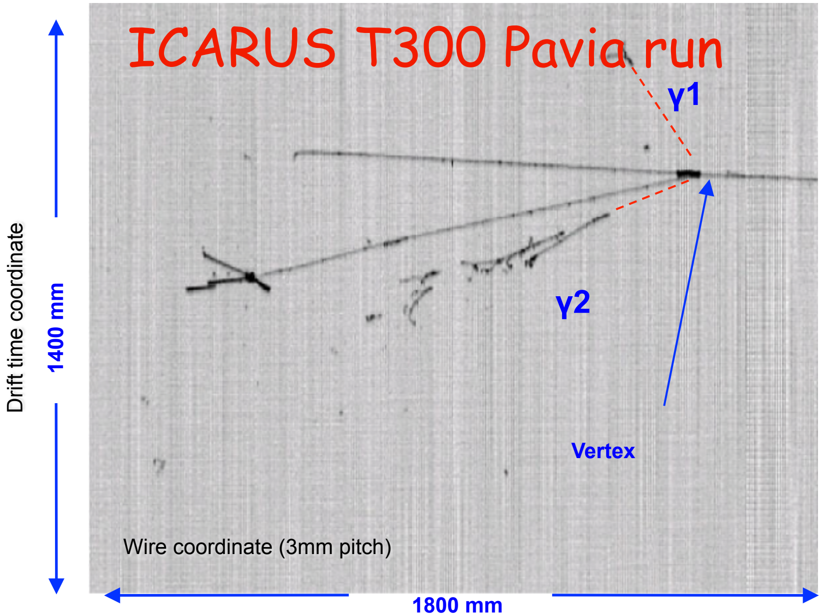


RESOLUTIONS

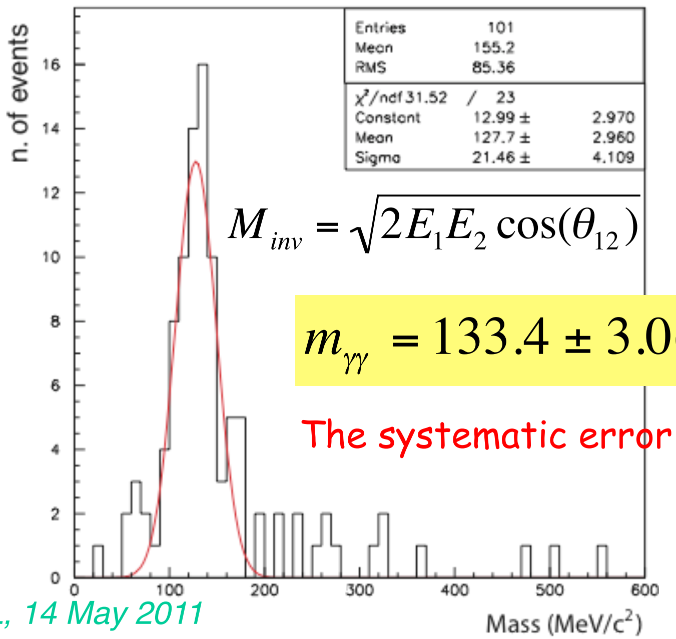
Low energy electrons:	$\sigma(E)/E = 11\% / \sqrt{E(\mathrm{MeV})} + 2\%$
Electromagnetic showers:	$\sigma(E)/E = 3\% / \sqrt{E(\mathrm{GeV})}$
Hadron shower (pure LAr):	$\sigma(E)/E \approx 30\% / \sqrt{E(\mathrm{GeV})}$

π^0 identification – electron / γ separation

Reconstruction of π^0-showers



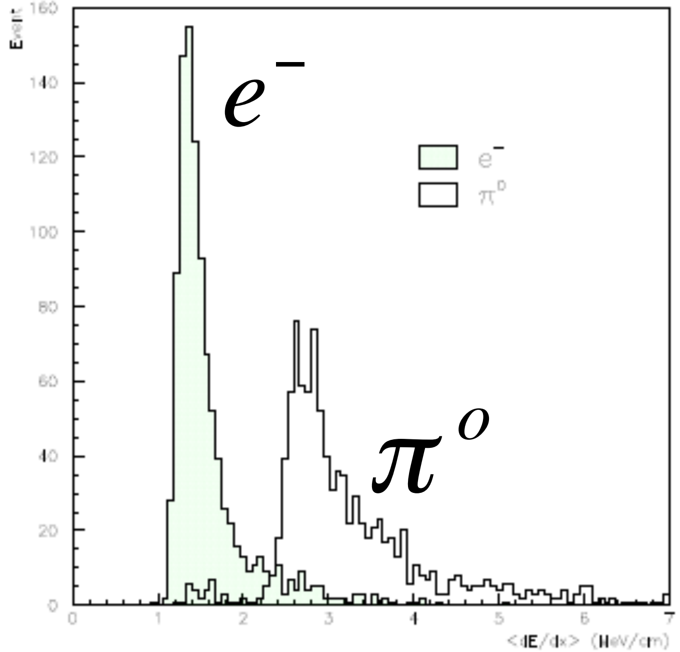
Electron shower events are extremely well identified experimentally, because of the ionization behaviour in the first cells after the vertex.



$$M_{inv} = \sqrt{2E_1E_2\cos(\theta_{12})}$$

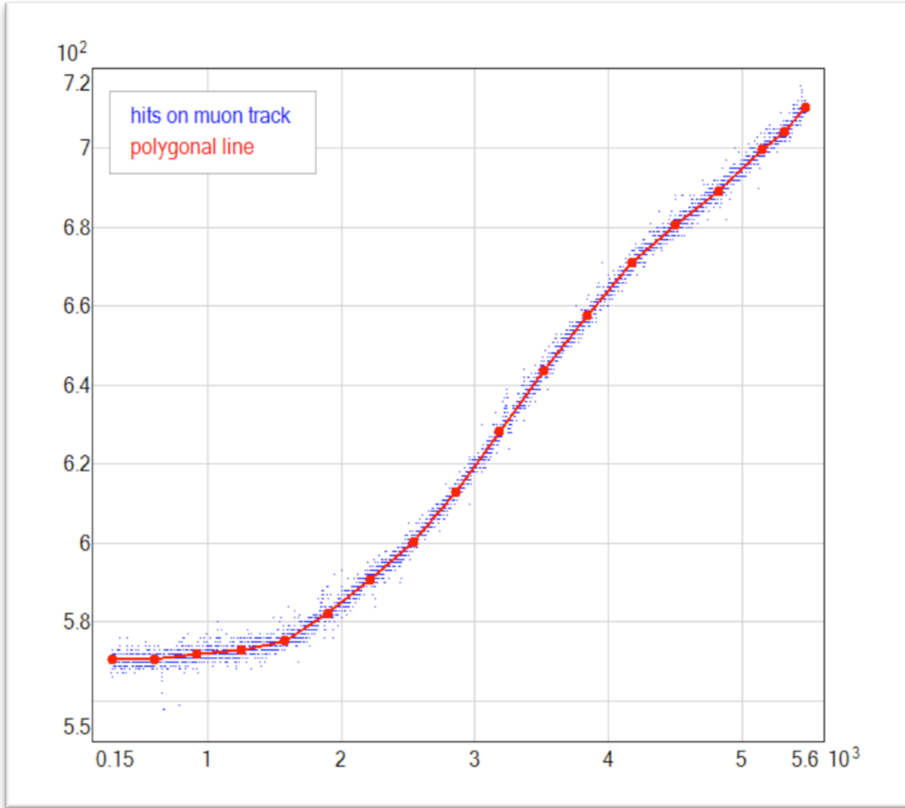
$$m_{\gamma\gamma} = 133.4 \pm 3.0(stat) \pm 4.0(sys)\,\mathrm{MeV/c^2}$$

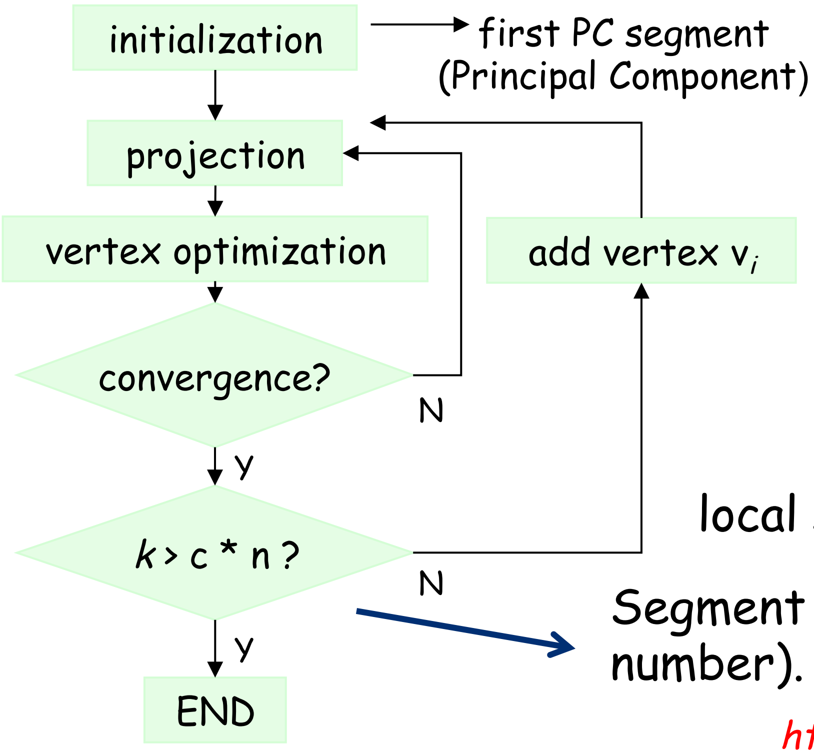
The systematic error mostly due to the calibration



3D reconstruction

- Complement of 2D reconstruction based on Polygonal Line Algorithm (PLA).
- 3D reconstruction: linking hit projections between views according to
  - drift sampling;
  - sequence of hits.





$$G(\mathbf{v}_i) = \frac{1}{n}\boxed{\Delta_n(\mathbf{v}_i)} + \lambda \frac{1}{k+1}\boxed{P(\mathbf{v}_i)}$$

local squared distance to hits

local angle penalty term

Segment number k exceeds given ratio $c * n$ (n track hits number). Longer tracks usually are more straight.

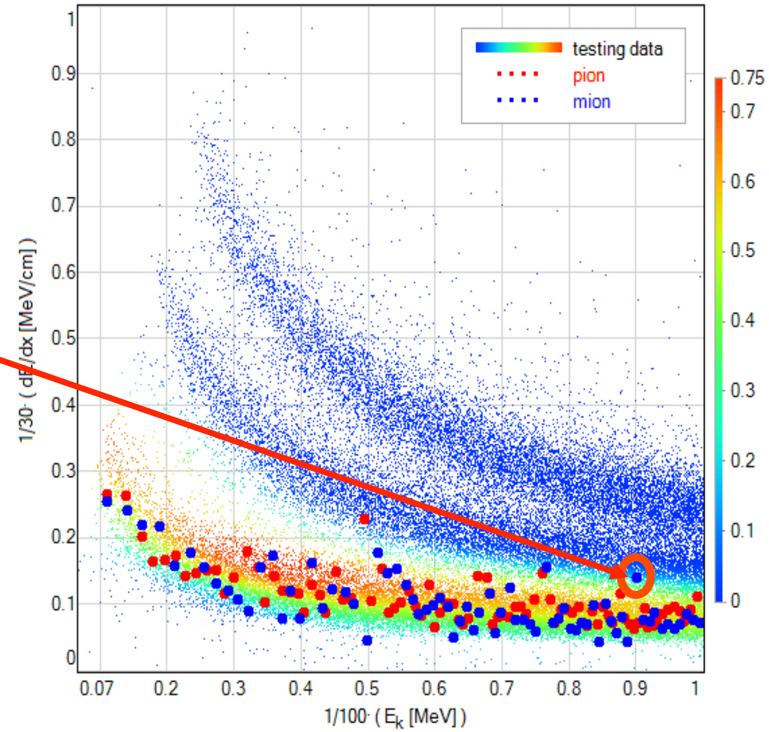
http://www.iro.umontreal.ca/~kegl/research/pcurves/

Neural network particle identification

- Particle identification based on:
  - distance between nearby 3D hits: dx
  - 3D hits and charge deposition : dE/dx
- Classify single i^{th} point on the track

  p_i : $[E_k, dE/dx] \rightarrow nn_i$: [P(p), P(K), P(p), P(μ)]
- Average M output vectors for the points

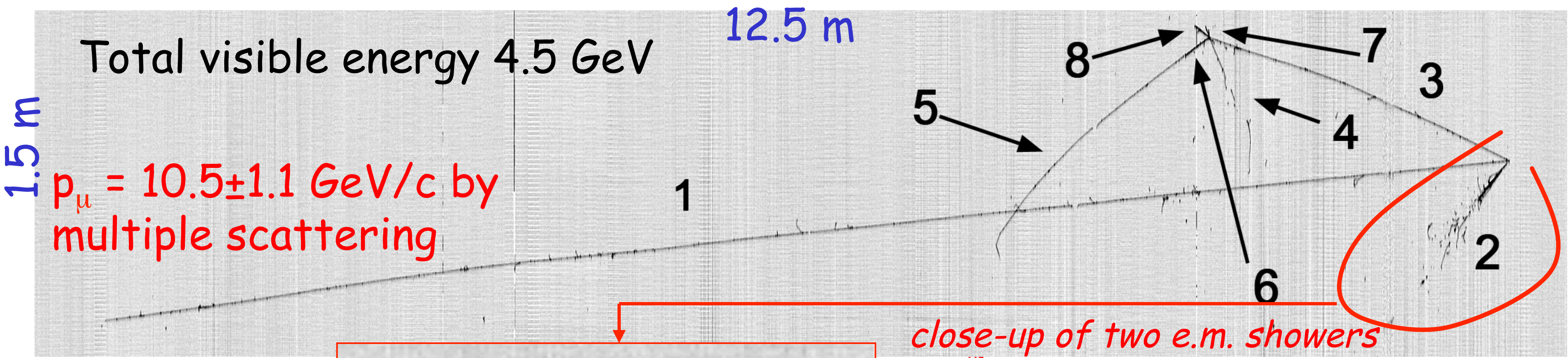
  NN = $S(nn_i)/M$
- Identify track as particle corresponding to max(NN)
- Energy reconstructed including quenching in simulation



pid / MC	p	K	π	μ	efficiency [%]	purity [%]
p	**481**	4	0	0	99.2	98.0
K	10	**380**	0	0	97.4	99.0
π	0	0	**196**	40	83.1	98.5
μ	0	0	3	**216**	98.6	84.4

Very high identification efficiency for p, k, pion+muon

LAr-TPC: powerful technique. Run 9927 Event 572

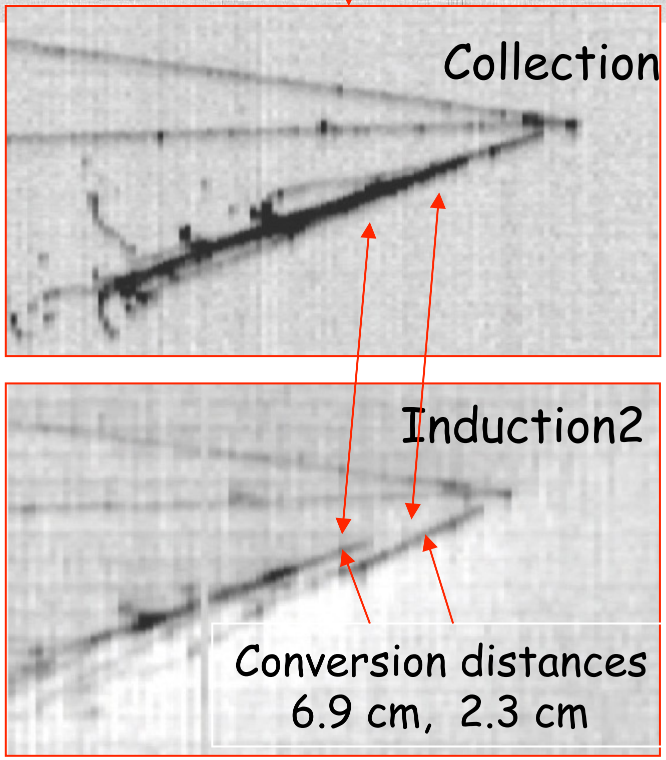


Primary vertex (A)

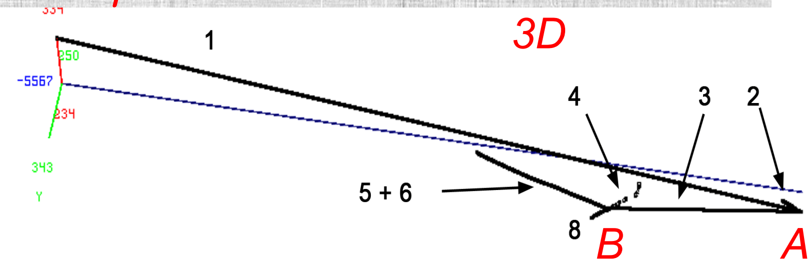
very long μ (1), e.m. cascade(2), pion (3).

Secondary vertex (B)

The longest track (5) is a μ coming from stopping k (6).
- μ decay is observed.

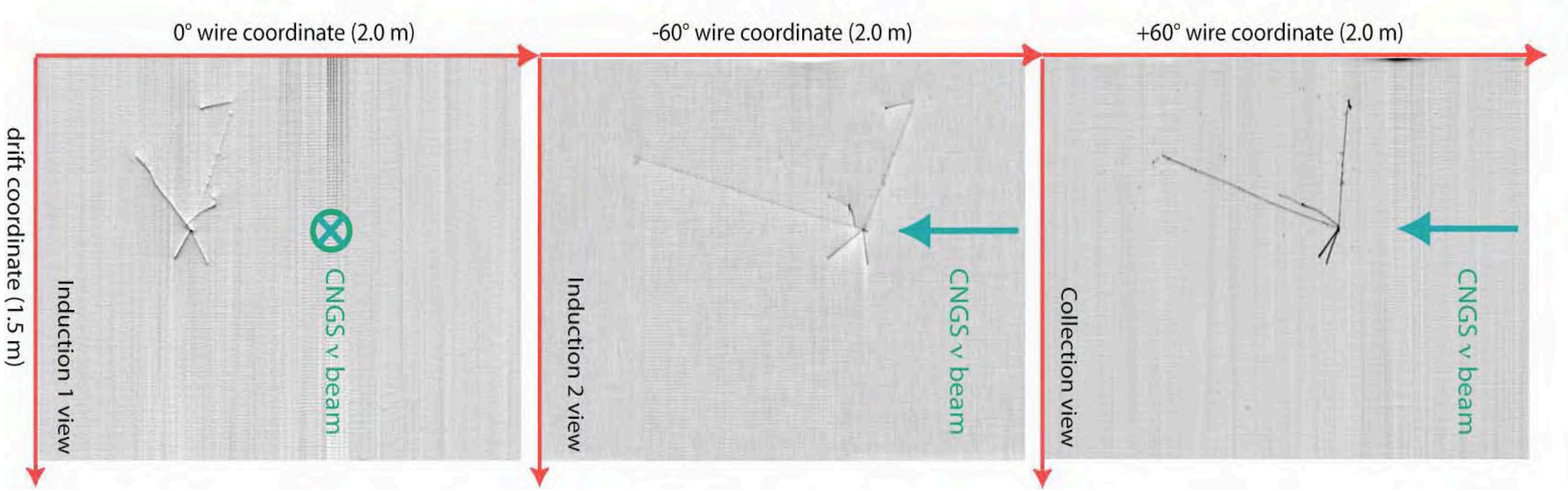


$M^*_{\gamma\gamma}$ = 125±15 MeV/c^2

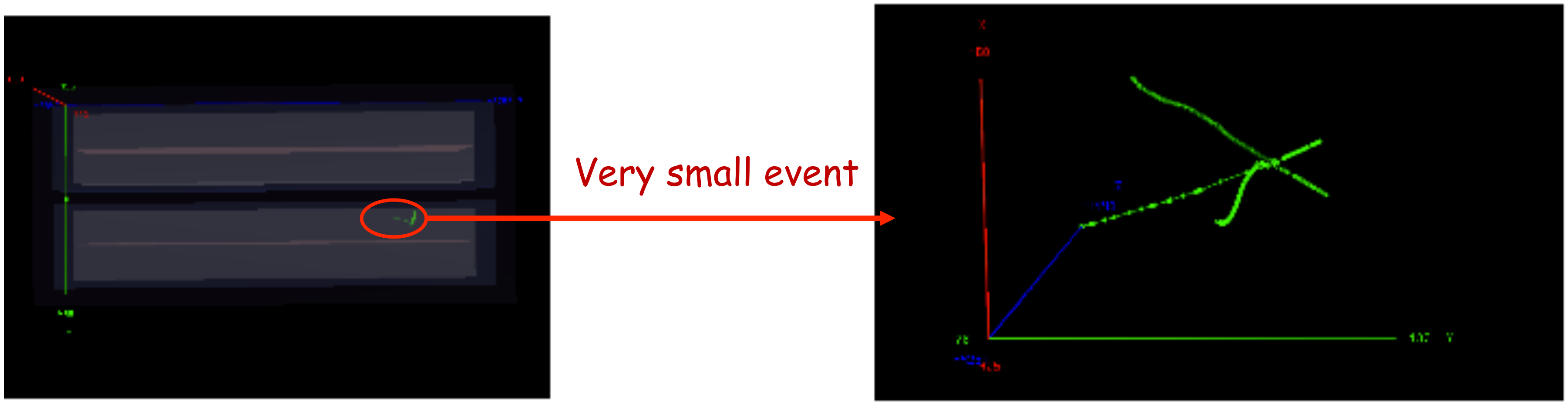


Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2 (π^0)	520.82	0.054	-0.420	-0.906
3 (π)	514.04	-0.001	0.137	-0.991
Sec.vtx.	797.			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

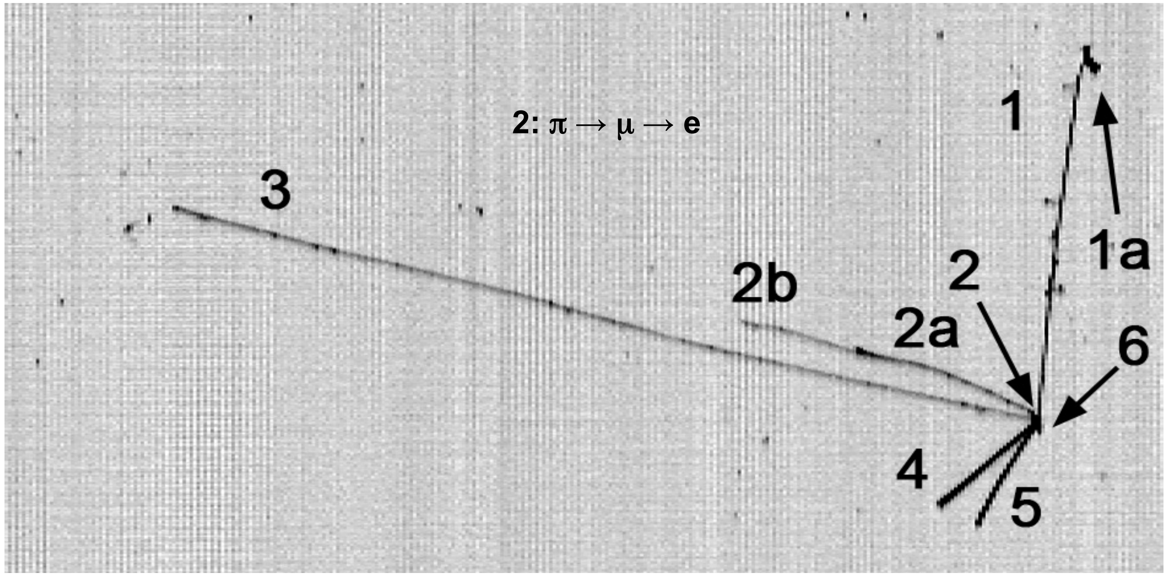
Atmospheric ν candidate

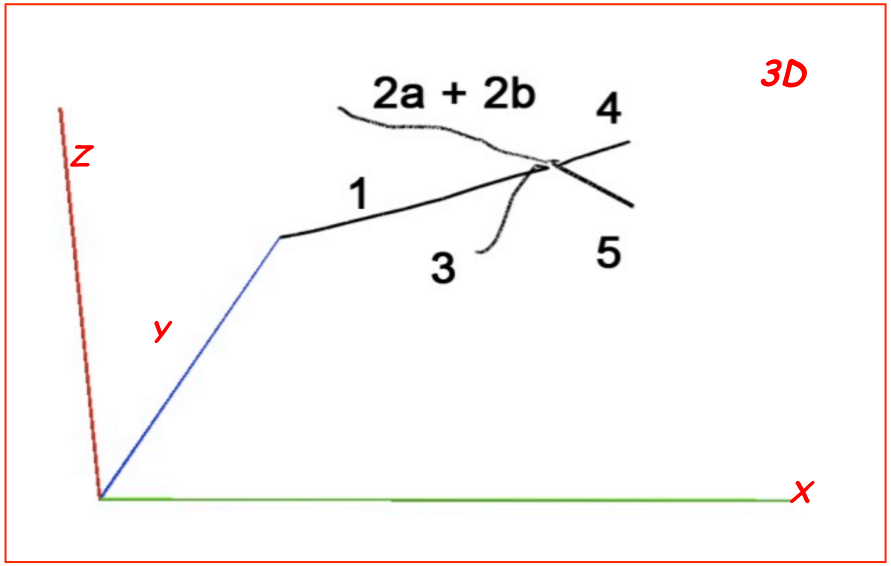


- Total visible energy: 887 MeV (including quenching and e⁻ lifetime corrections).
- Out-of-time from CNGS spill AND angle w.r.t. beam direction: 35°.



Run 9392 Event 106



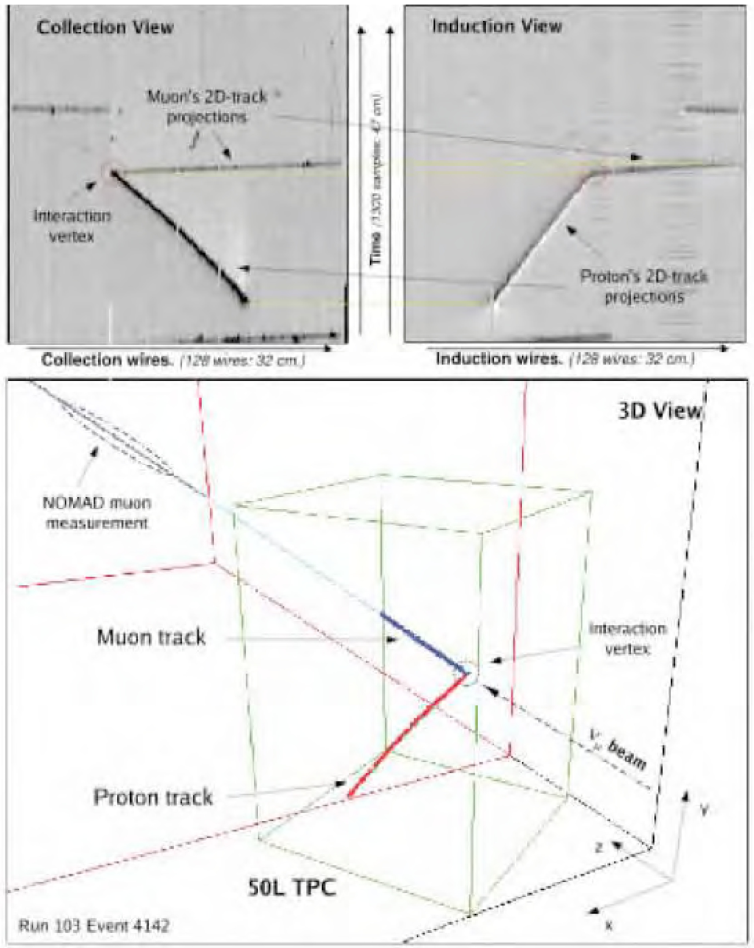


Track	E_k [MeV]	Range [cm]
1 (prob. π, decays in flight)	136.1	55.77
2 **(π)**	26	3.3
2a **(μ)**	79.1	17.8
2b **(e)**	24.1	10.4
3 **(μ)**	231.6	99.1
4 **(p)**	168	19.2
5 **(p)**	152	16.3
6 (?) (merged with vtx)		2.9

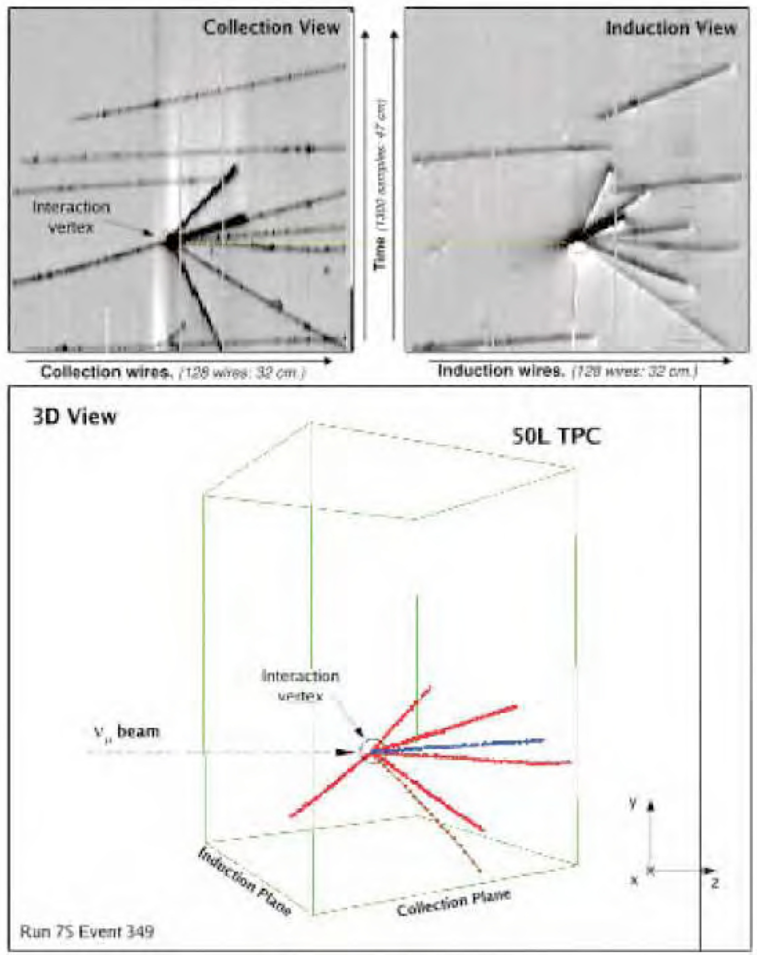
- Total deposited energy: 887 MeV
- Total reconstructed momentum: 929 MeV/c at about 35° away from the CNGS beam direction

Neutrino events in the 50 l LAr-TPC @ CERN WANF

- Example of 3D reconstruction in the vertex region of:
  - quasi-elastic event with a muon and a proton recoil track (A)
  - a multi-prong neutrino event



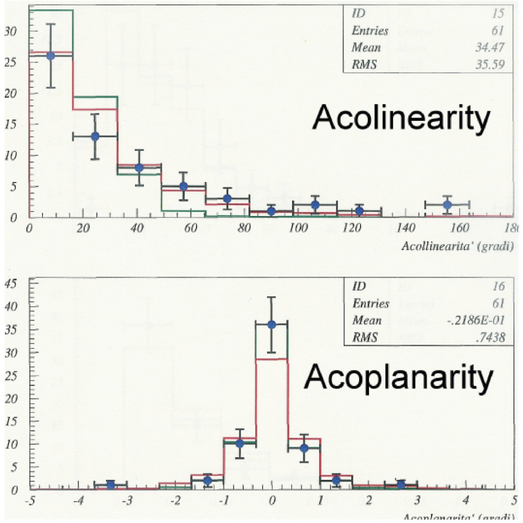
(A)

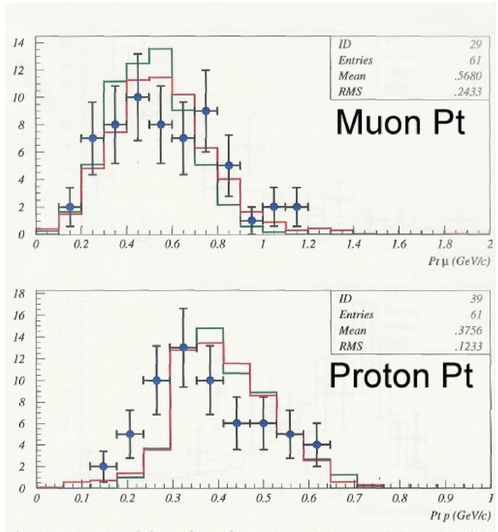


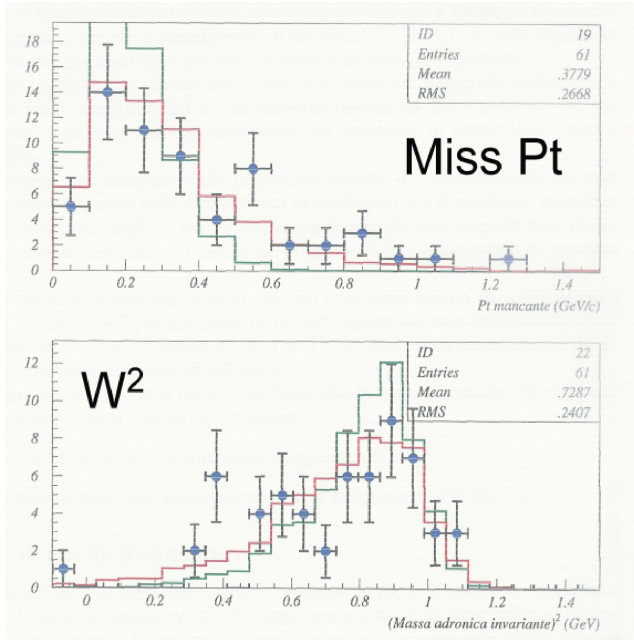
(B)

Quasi-elastic final state event reconstuction

- Quasi-elastic muon neutrino events in LAr have been reconstructed in the 50 litre ICARUS LAr-TPC exposed to the CERN-WANF beam in coincidence with the NOMAD experiment.
- Muon momentum measured by NOMAD for matching tracks
- Simulations, accounting for Nuclear Fermi motion and re-interactions in nuclei, found in good agreement in a ~ 10^2 pure lepton-proton final state events with 1 proton TP > 50 MeV (range > 2 cm) and any number protons TP< 50 MeV.







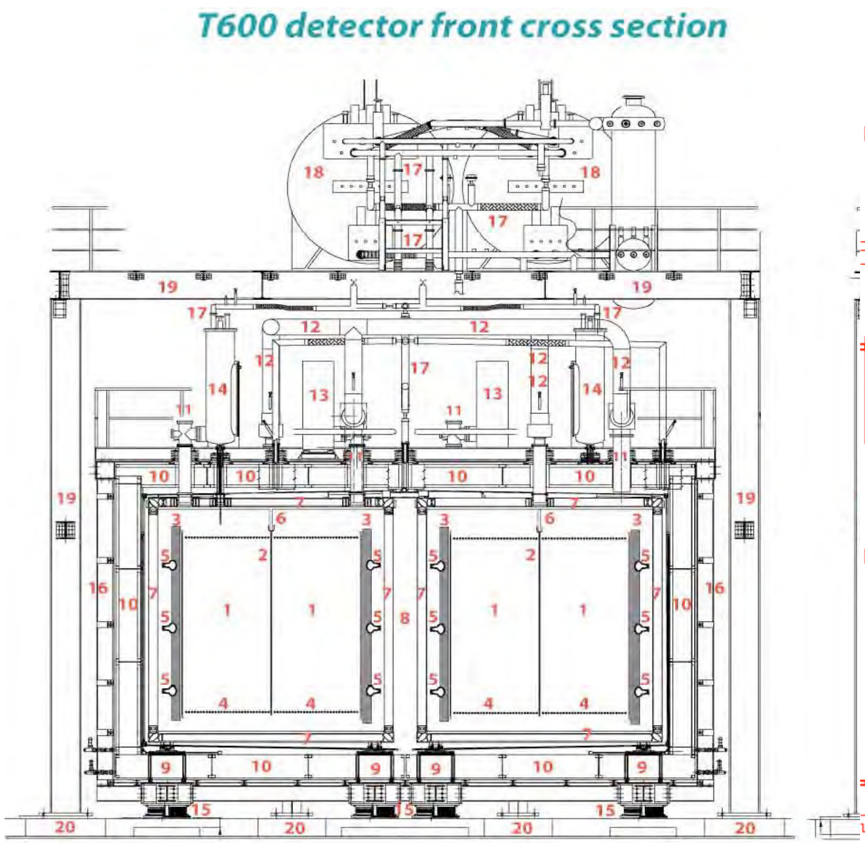
T600 transport from LNGS to CERN and T150 construction

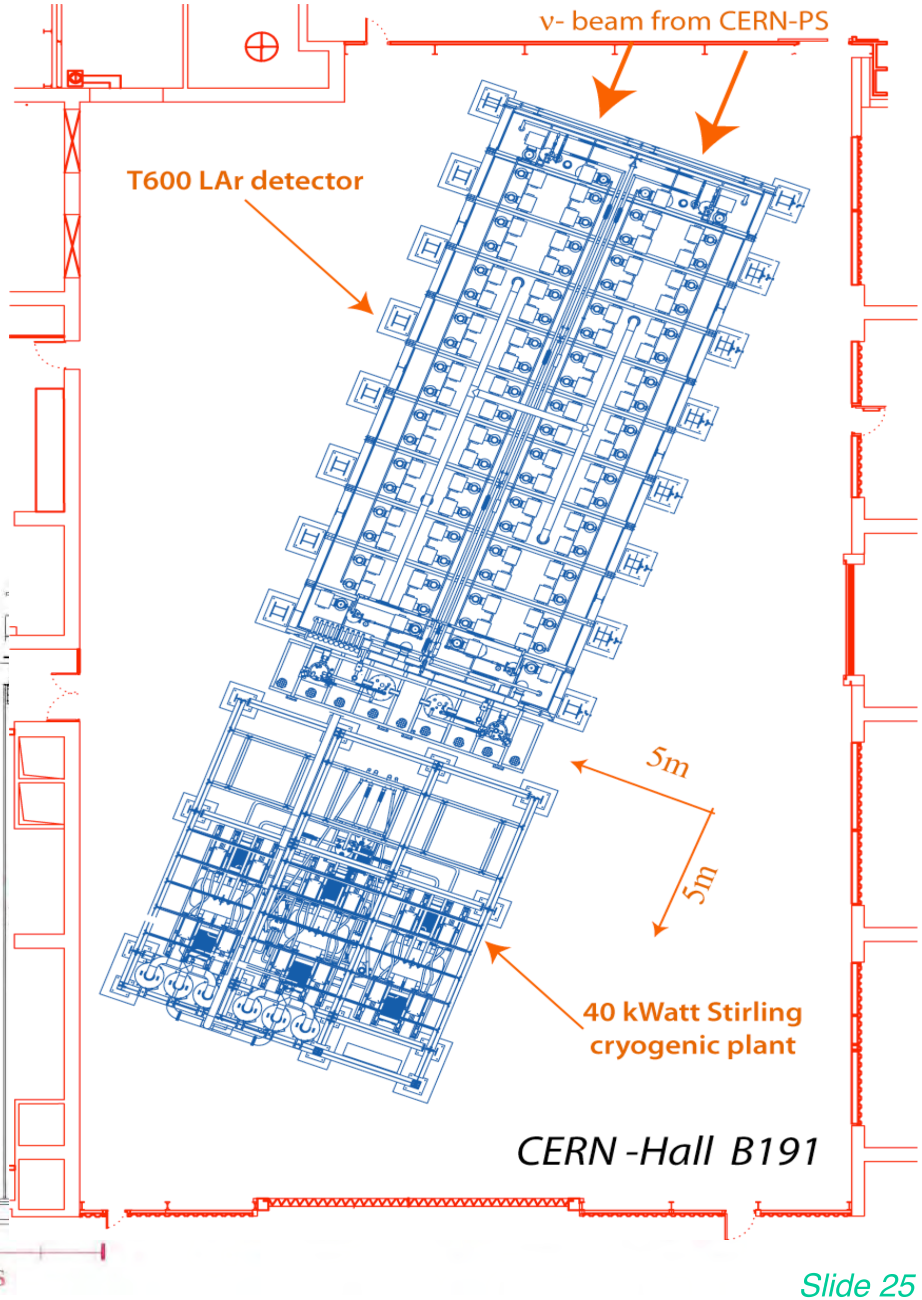
- According to the present programme CERN will provide 2 years full intensity beam to ICARUS before 2013 stop when T600 can be transported to CERN, ensuring the new experiment operation again in 2014.
- The 2 sub-modules can be extracted from thermal insulation, dismounted, transported and reconstructed in Hall B-191 about 12-14 months in a new insulation vessel that could be assembled in situ.
- A large number of additional components can be disassembled/transported: electronics for DAQ, ancillary systems located in three levels of the supporting structure surrounding the T600 and LN_2 liquefaction system.

- The existing wire chambers tooling and wiring infrastructures can be used for the construction of the T150 Near Detector in a two-three year time scale.
- Cryogenics, PMTs, front-end electronics, DAQ and ancillary equipments, can be replicated according to the downscaled detector mass: one GAr and LAr recirculation system, two LN2 recondenser units, 14200 electronic channels with 25 electronic racks and 30 PMT's of 8" diameter.
- Some improvement/simplification may be studied and implemented.

The ICARUS T600 as "Far" detector in Hall B191

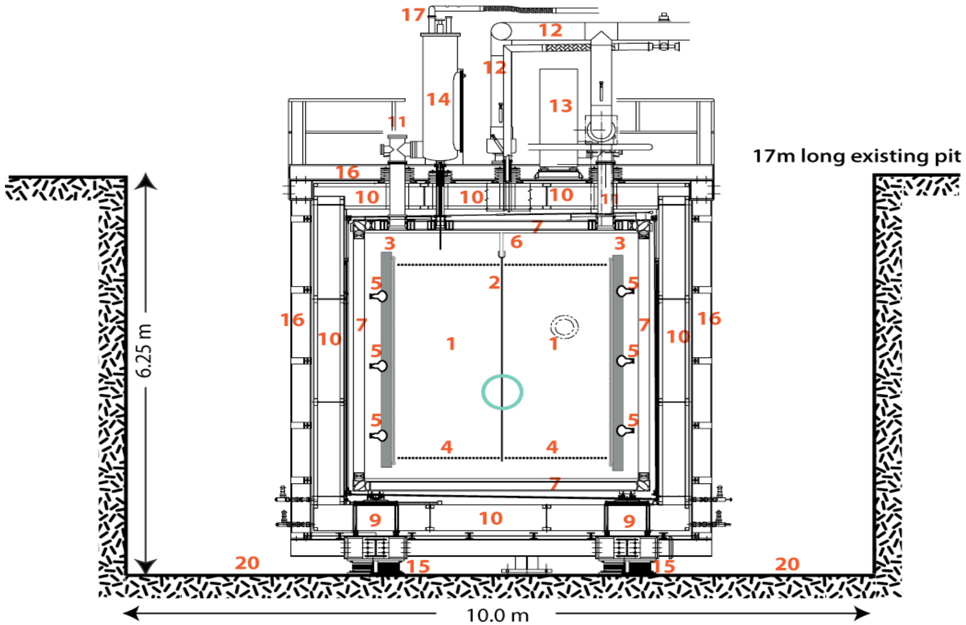
- The T600 detector could be moved and operated at CERN in the old BEBC experimental hall (Hall 191) without major modifications

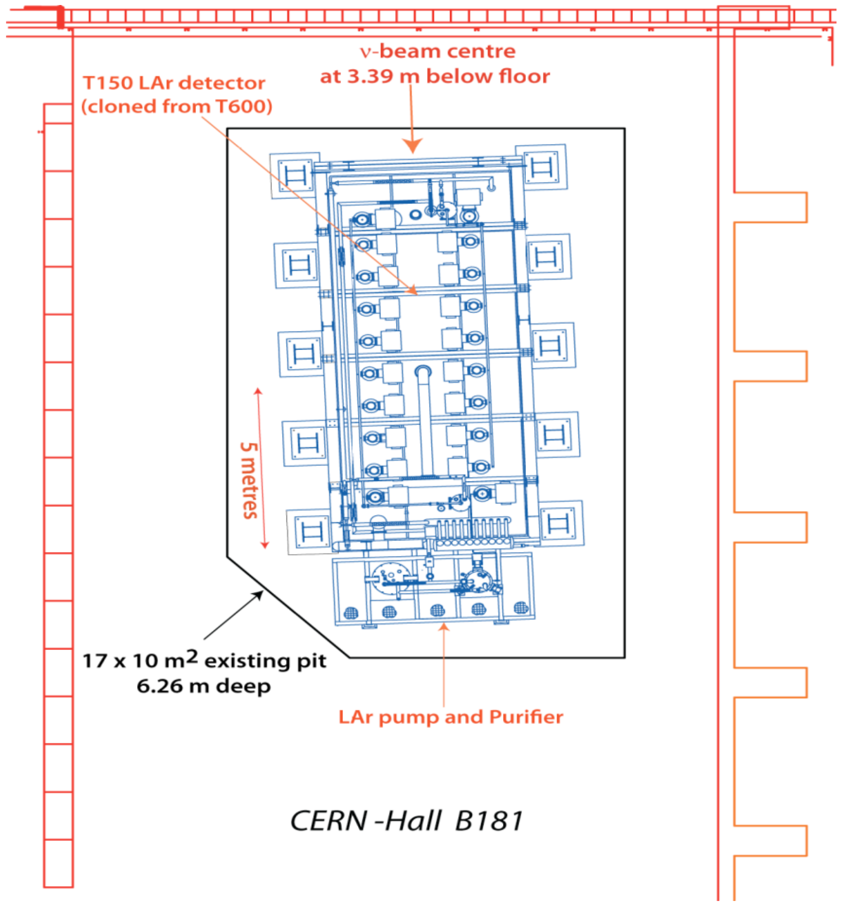




The additional T150 detector (to be constructed)

- Maximum of similarity with Far: a clone of a single semi-module, length reduced by a factor 2 (about 12 m) keeping untouched the inner detector layout (TPC structure) with a mass of 150 t.
- Near detector dimensions (1 m passive insulation): 13 x 6 m^2 with 6 m height. It fits perfectly the existing basement pit of Hall 181, previously used for neutrino exps.

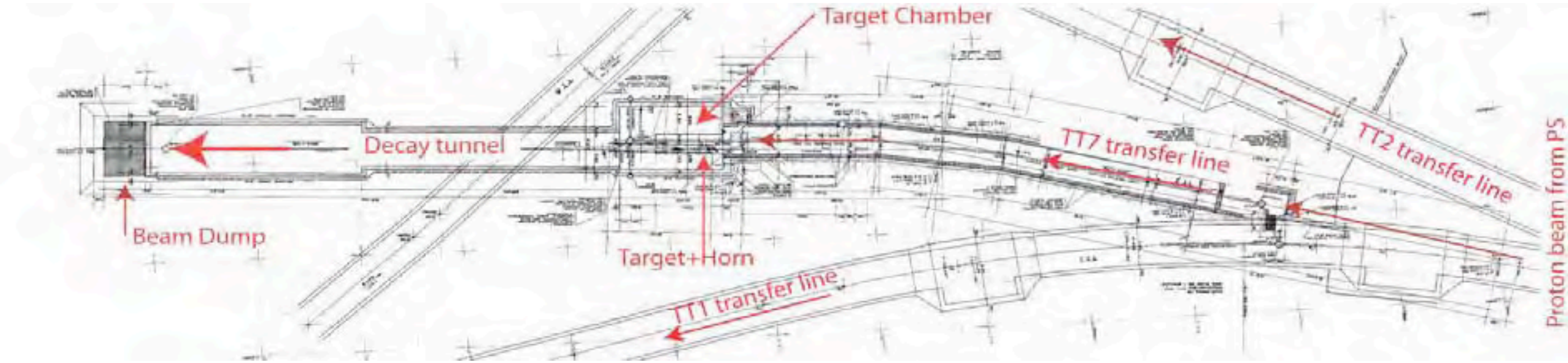




Refurbishing the old line used by BEBC

- The PS proton beam at 19.2 GeV/c is extracted via TT2, TT1 and TT7
- The magnetic horn is designed to focus particles of momentum ≈ 3GeV/c
- The decay tunnel is about 50 m long, followed by an iron beam stopper

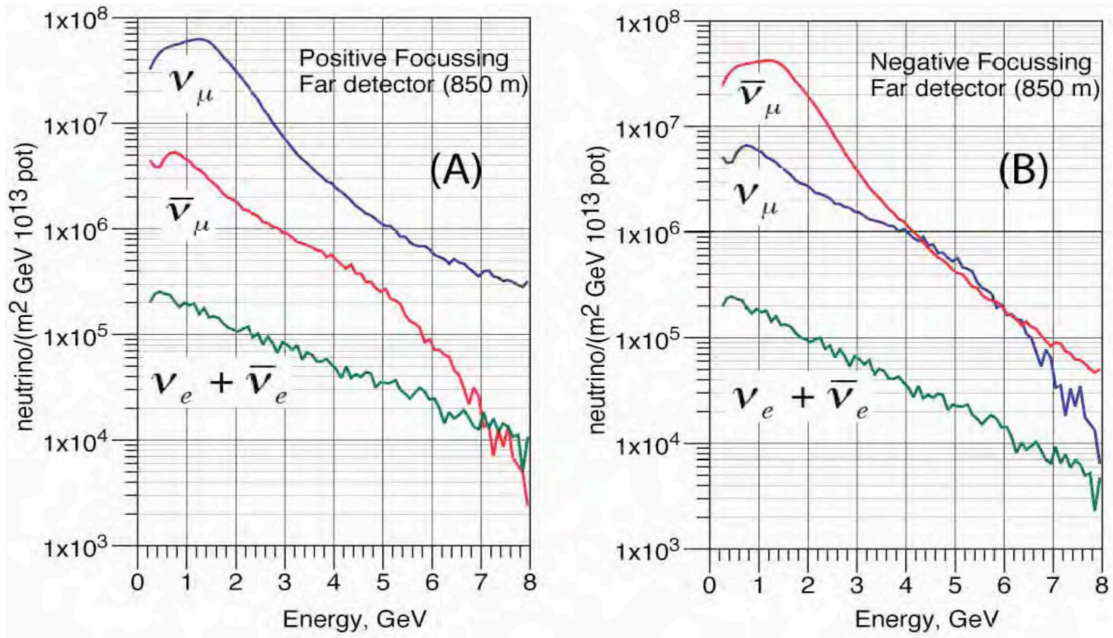
PS-180 $\nu\mu \rightarrow \nu e$ (BEBC)



Expected CERN PS neutrino beam spectra and rates

- Starting point: PS-180 experiment and I216 /P311 proposal

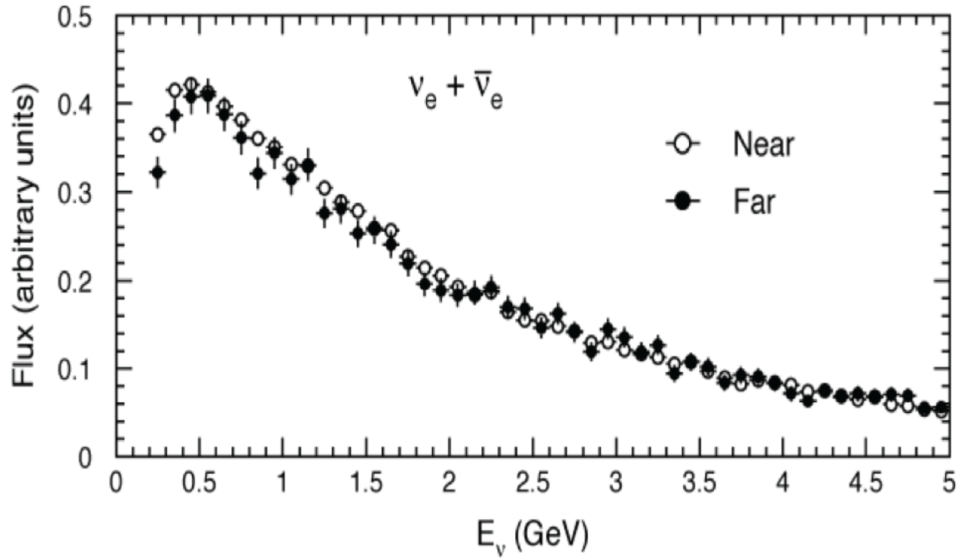
- 19.2 GeV protons – 1.25 10^{20} pot/ years (30 kW average power)
- Old target/horn design
- Anti-ν_μ CC rate ~ 1/3.5 of the one of the neutrino case, due to π^-/π^+ production < 1 and smaller anti-ν/ν x-sections < 0.5

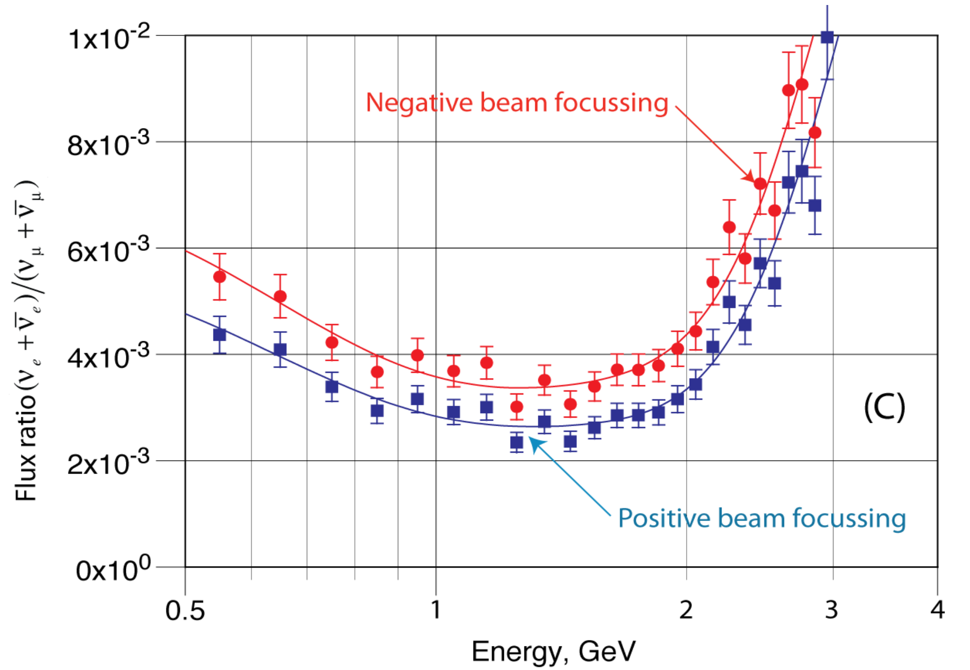


2 year PS neutrino beam	Neutrino focus		Anti-neutrino focus	
	Far	Near	Far	Near
Fiducial mass	500t	150t	500t	150t
Distance from target	850 m	127 m	850 m	127 m
ν_μ interactions	1.2×10^6	18×10^6	2.0×10^5	2.3×10^6
QE ν_μ interactions	4.5×10^5	66×10^5	87000	1.0×10^6
Events/burst	0.17	2.5	0.03	0.3
Intrinsic ν_e from beam	9000	120000	2000	29000

The CERN-PS ν_e and anti-ν_e spectral shape

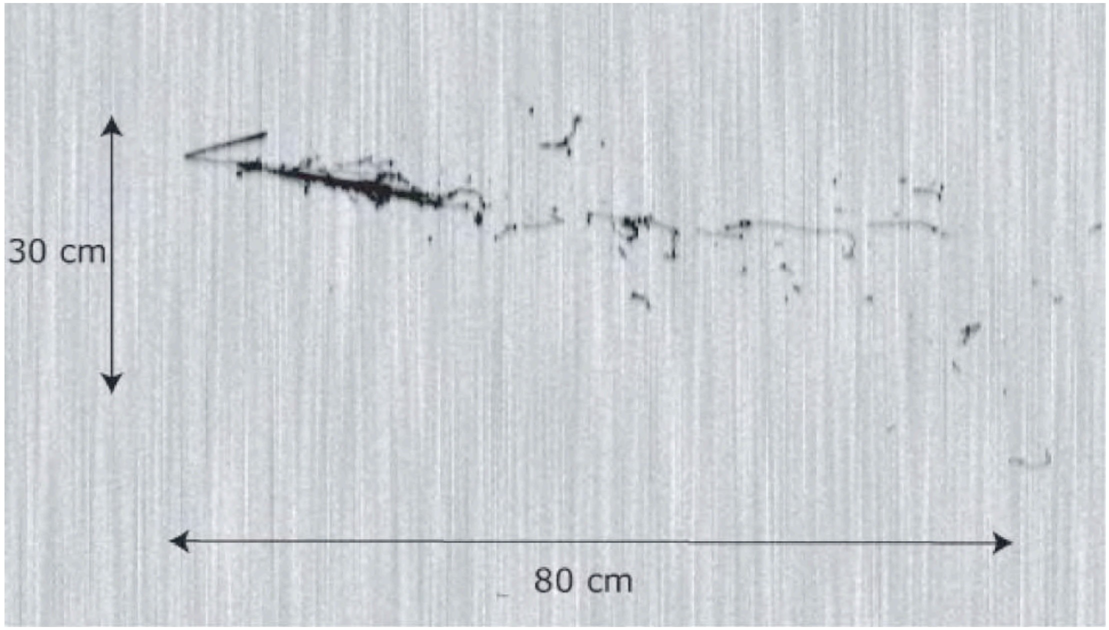
- The ν_e spectra are expected very closely identical in the "Near" and "Far" positions.
- This specific property of the electron neutrino is due to the fact that they are produced essentially by the K-decays with a much wider angular distribution.
- The effect is enhanced by the fact that both detectors have been designed with identical experimental configurations.
- (anti-ν_e + ν_e) in anti-ν_μ ~ 1.5 of the ν_μ case





ν_e CC interaction at ~ 1.5 GeV

- At these energies, electron identification and energy reconstruction of ν_e interactions is ensured with ~5 X_0 (X_0=14cm) longitudinal cut and ~2 X_0 side cut of the sensitive volume are performed, corresponding to a fiducial volume of ~ 80 % of the active one.



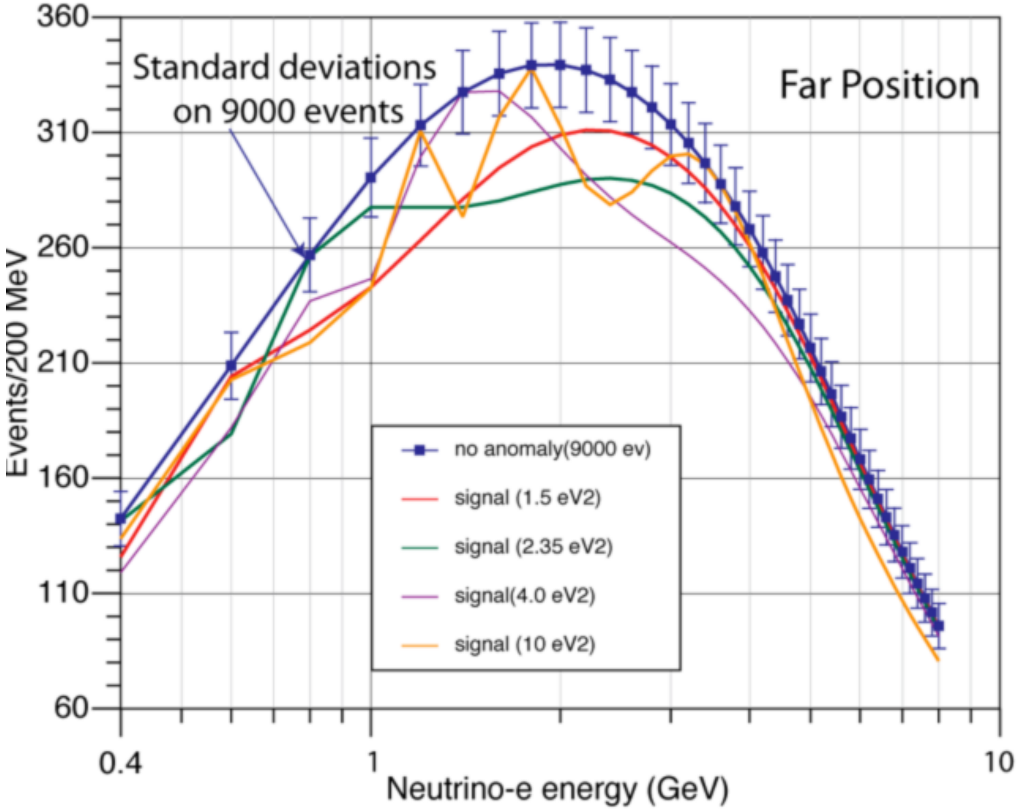
π^0 from NC are rejected by photon vertex identification, invariant mass reconstruction and dE/dx measurement: the expected π^0 mis-interpretation probability is 0.1 %, with ν_e detection efficiency of 90 % within the fiducial volume.

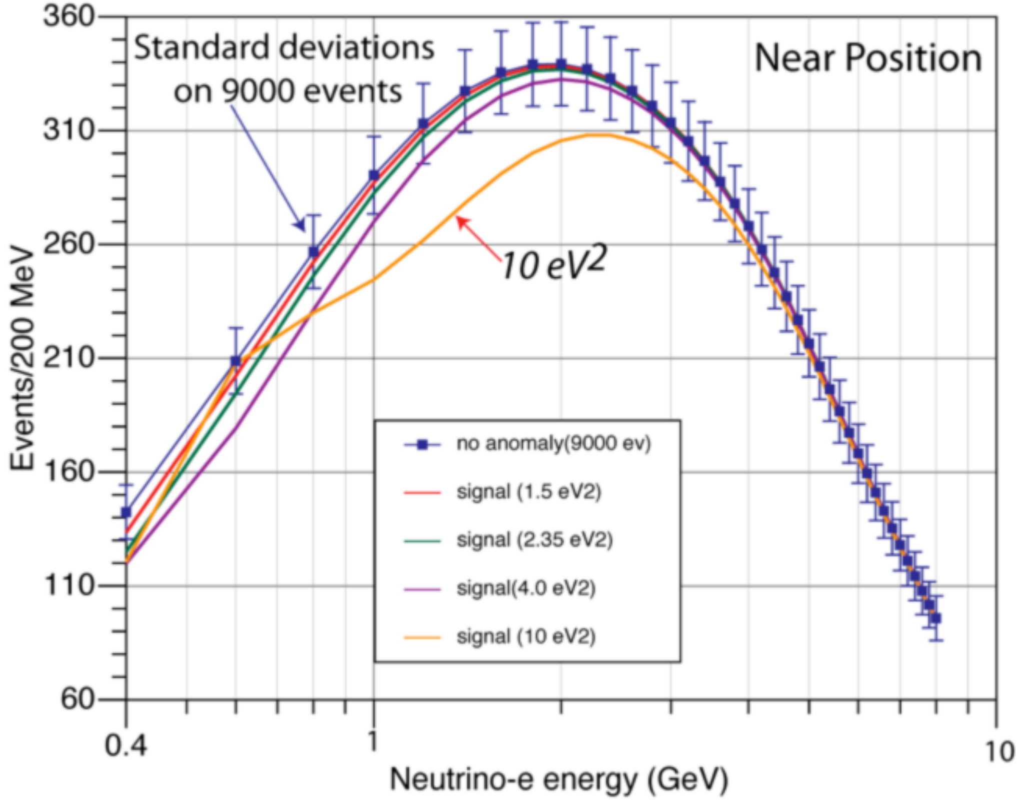
With these fiducial cuts, the expected ν_e energy resolution is around 14 %

Signal selection and background rejection

- The energy resolution and detector granularity are largely adequate for the lower energy range (1 ÷ 3 GeV) relevant for the present proposal.
- A key issue of the experiment is the detection capability of the genuine ν_e events and the very high level of rejection of the associated background events, in primis from the π^0 decay.
- The LAr-TPC detector appears very well suited for this purpose, because of its excellent imaging and calorimetric capabilities, which allow very efficient electron-π^0 separation, together with unambiguous electron identification.
- In the LAr-TPC all reaction channels with electron production can be analyzed without the need to restrict the search to the quasi-elastic channel, which accounts for about slightly less then one half of the events.
- Moreover, events due to neutral currents are also very well identified and can be rejected to a negligible level

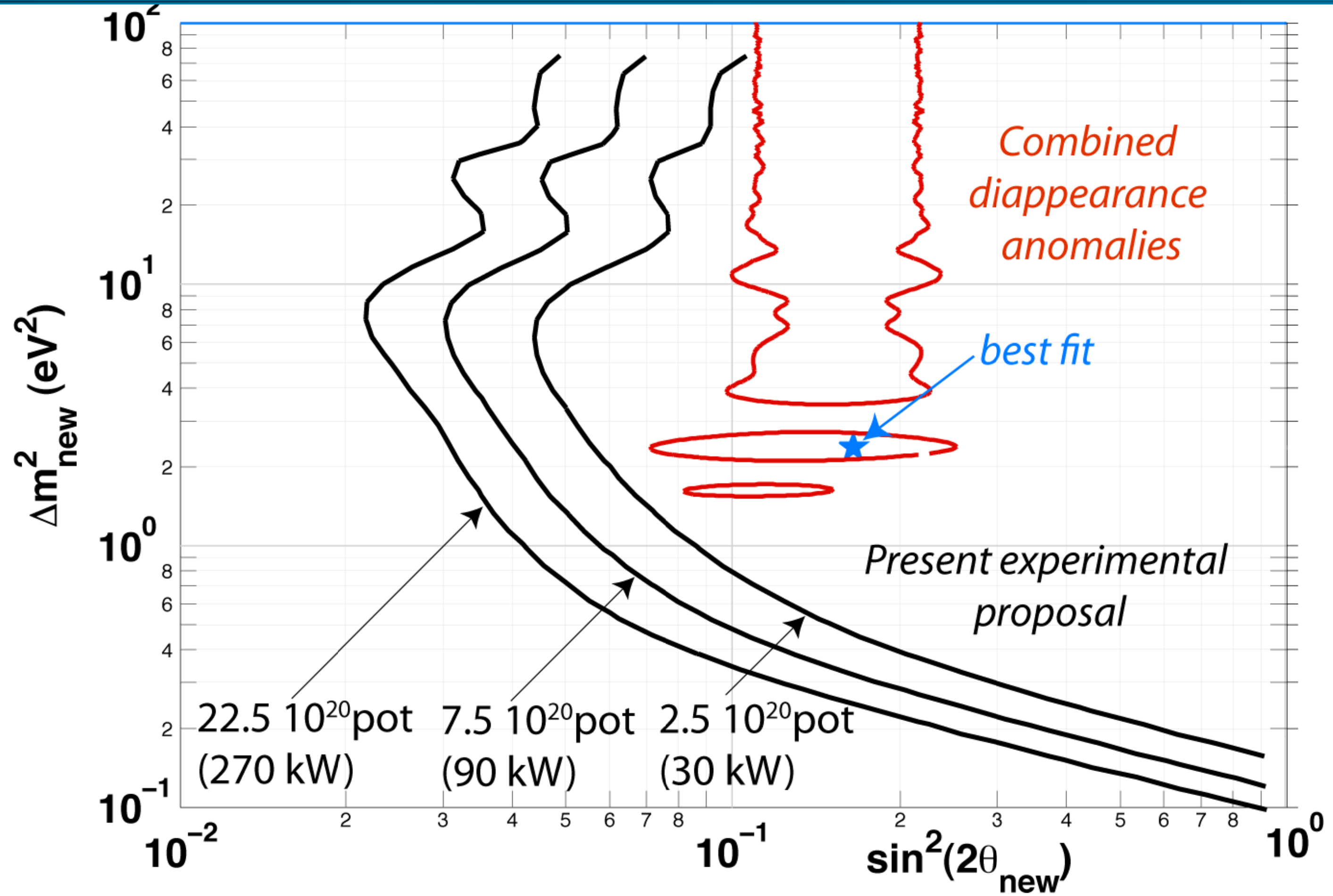
Sensitivity to ν_e disappearance signals





The energy distributions of the electron neutrino events is shown in (a) and (b) respectively for the "Far" and "Near" and a number of possible values in the region of $\Delta m^2 > 1 eV^2$ and $sin^2(2\theta) \approx 0.16$ for 9000 neutrino events.
If such a large mass difference will have an important role in the explanation of the existence of the Dark Mass in the Universe.

Sensitivity to disappearance anomalies



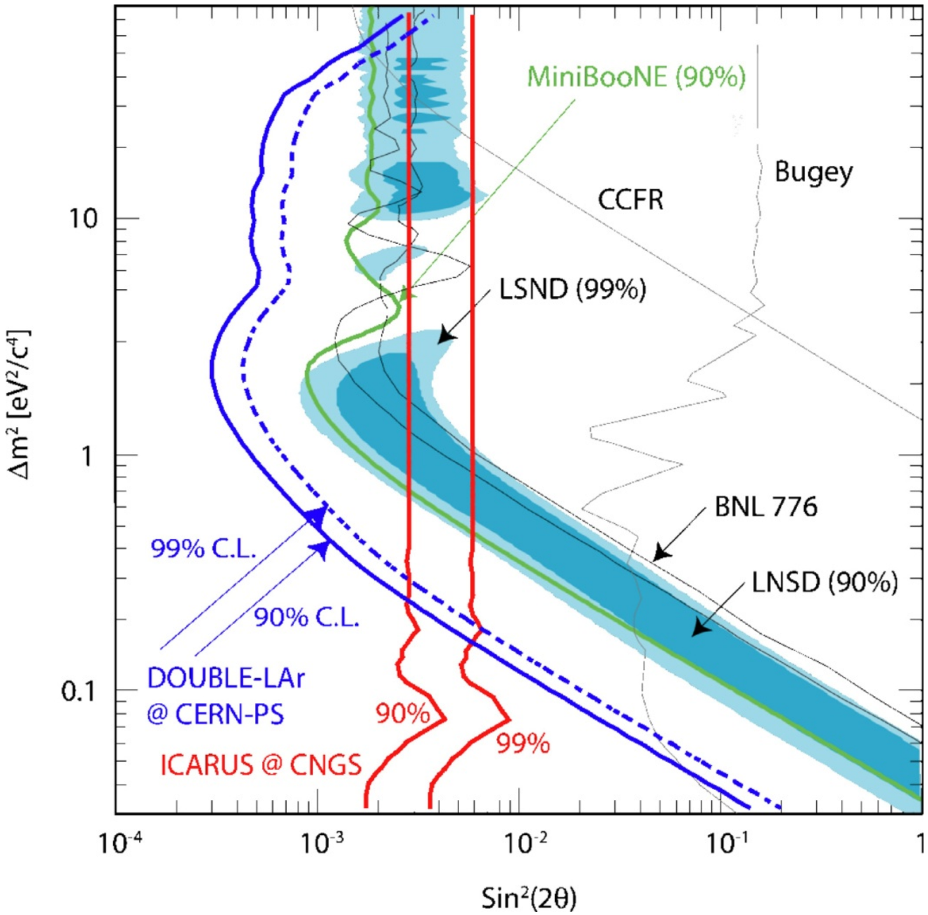
- Sensitivities (90% CL) in the $\sin^2(2\theta_{new})$ vs. Δm^2_{new} for an integrated intensity of (a) 2.5 10^{20} pot (30 kW average CERN/PS beam intensity), (b) a fully dedicated (90 kW) neutrino beam and (c) a 270 kW curve. They are compared (red) with the “anomalies” of the reactor + Gallex and Sage experiments. A 1% overall and 3% bin-to-bin systematic uncertainty is included (for 100MeV bins).

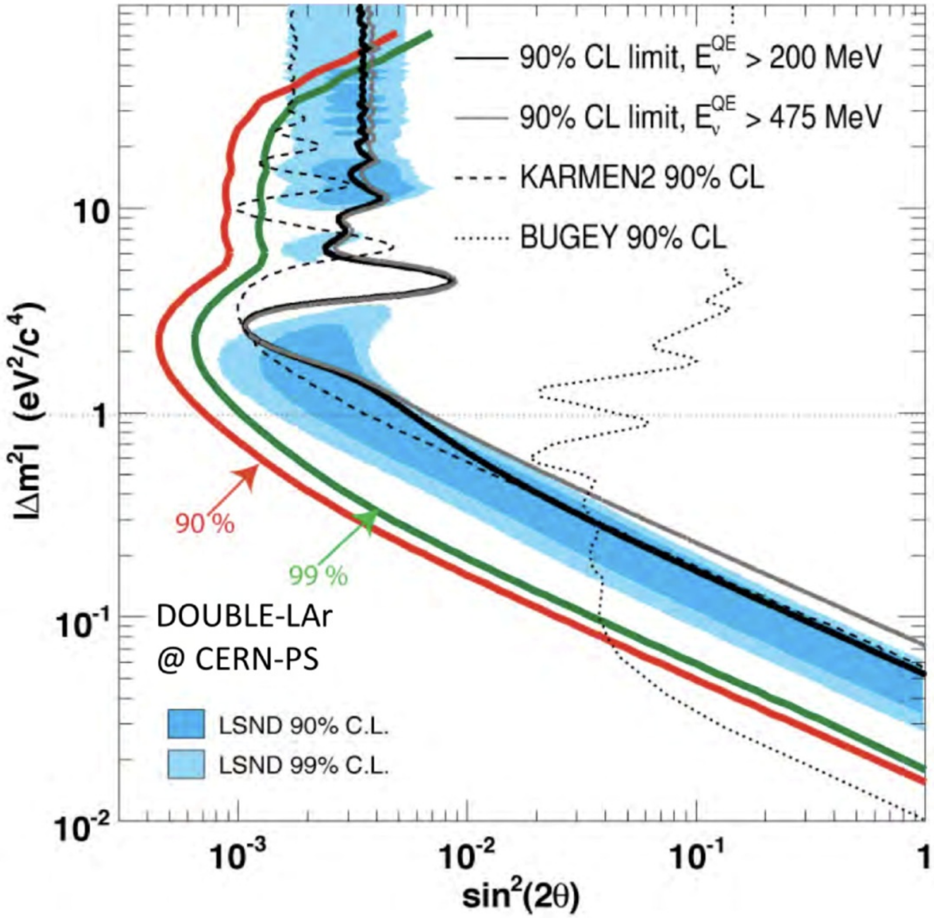
Expected signal for LSND/MiniBooNE anomalies

- Event rates for the near and far detectors given for 2.5 10^{20} pot (30 kW beam power) for E_ν < 8 GeV. The oscillated signals are clustered below 3 GeV of visible energy.

	Neutrino focus		Anti-neutrino focus	
	Far	Near	Far	Near
Fiducial mass	500t	150t	500t	150t
Distance from target	850 m	127 m	850 m	127 m
ν_μ interactions	1.2×10^6	18×10^6	2.0×10^5	2.3×10^6
QE ν_μ interactions	4.5×10^5	66×10^5	87000	1.0×10^6
Events/burst	0.17	2.5	0.03	0.3
Intrinsic ν_e from beam	9000	120000	2000	29000
Intrinsic ν_e from beam (E_ν < 3 GeV)	3900	54000	880	13000
ν_e oscillations: $\Delta m^2 = 0.064\ eV^2$; $\sin^2 2\theta = 0.96$	2980	1250	465	140
ν_e oscillations: $\Delta m^2 = 0.4\ eV^2$; $\sin^2 2\theta = 0.02$	2083	2340	330	115
ν_e oscillations: $\Delta m^2 = 2.\ eV^2$; $\sin^2 2\theta = 0.002$	1194	1050	230	58
ν_e oscillations: $\Delta m^2 = 4.2.\ eV^2$; $\sin^2 2\theta = 0.0066$	3350	25050	490	3220
	2 y		2 y	

Comparing LSND sensitivities *(arXiv:0909.0355)*





Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (left) for 2.5 10^{20} pot (30 kW basic option) and twice as much for anti-neutrino (right). The LSND allowed region is fully explored both for neutrinos and anti-neutrinos. The T600 expectations from one year at LNGS are also shown.

Status of advancement of the Proposal

- A Memorandum has been sent to the CERN-SPS-C dated on March 9th describing a possible continuation of the ICARUS programme at the CERN-PS, with the following three major new steps:
  - the construction, or better the reconstruction of a CERN-PS horn focussed neutrino beam;
  - the enlargement and the reformulation of the collaboration to a wider international team; and
  - the formulation and approval of a formal proposal to the SPS-C, ensuring the availability of appropriate human and financial resources.

- The response of the SPS-C has been positive on all three issues, namely
  - *The SPS-C recognises the physics motivation and the opportunity offered by the ICARUS technology and availability.*
  - *The Committee will review the project once a detailed proposal is available.*
  - In addition *CERN is prepared, within its available resources, to study the re-building of the neutrino beam*.
- Therefore requirements are now fulfilled in order to move ahead towards the detailed proposal.

On going activities

- Optimization of the target/focusing optics will be investigated in collaboration with the CERN-PS neutrino facility team

- In parallel detailed study of experiment performance is proceeding:
  - Full detector simulation including true detector response
  - ICARUS event reconstruction machinery
  - Full oscillation analysis.

- Additional studies to possibly disentangle "ν_e appearance" from "disappearance anomalies" are also under way, exploiting the high statistics (anti-) ν_μ CC and NC spectral shapes.

- In addition: interest to complement the LAr TPC's with a down-stream muon spectrometer has been recently expressed to introduce charge measurement and extend momentum measurement in ν_μ interactions (see L. Stanco talk at the "Beyond3nu" workshop held at LNGS on May 4-5, 2011). Possible complementary for the ν_μ disappearance oscillation search.

The present ICARUS Collaboration: to be extended

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Thank you !